

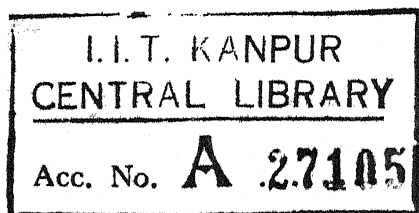
**EVALUATION OF PORE-SIZE DISTRIBUTION OF POROUS  
MEDIA FROM CAPILLARY PRESSURE CURVES—  
A NETWORK APPROACH**

A Thesis Submitted  
In Partial Fulfilment of the Requirements  
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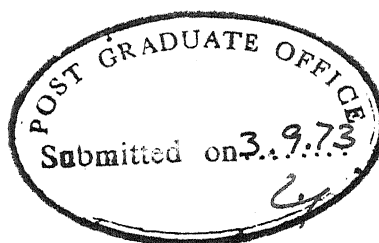
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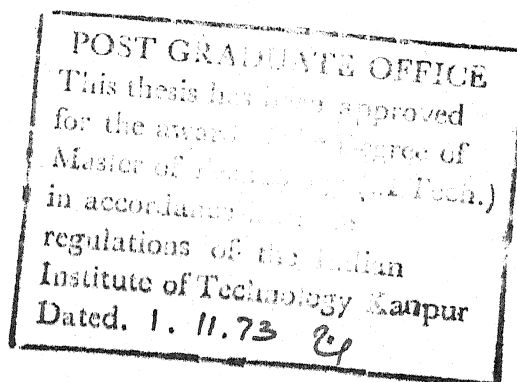
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CERTIFICATE

It is certified that this work has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Porous media are interconnected networks of void space of multitude shapes and sizes. Attempts in developing an analytical expression for the fluid flow behaviour through them have not been satisfactory to-date. The classical model of the bundle of tubes is too simplified a model to be realistic and useful. In the present work the flow behaviour of porous media has been modelled by a network of interconnected tubes of different sizes. An attempt has been made to extend the concept of relating pore-size distribution (both volumetric and number) to the capillary character of the network. The validity of 'ink-bottle' effect has been tested by the comparison of capillary pressure data with the actual tube size distribution of the network.

The extent of inter connection between the pores in a network is found to be a very important factor influencing the shape of the  $P_c$  curves. Therefore, any model of porous media based on bundle of tubes concept is likely to give erroneous results. Fatt's model, however, may be used with modified value of the exponent (between -2.5 to -3.5) to give better result for the number distribution. Similarly while correcting the measured pore-size distribution (volumetric) by Meyer's method, it has been found that the relation  $V \propto r^{1.5}$  improves the interpretation. These values for exponents have been obtained

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for networks with six tubes (on the average) meeting at a node point. The modified values of exponents perhaps correct for inter\_connection between the pores.

## CHAPTER 1

### INTRODUCTION

Porous media, whether in the form of natural rocks or particulate aggregates such as powder-packs, have quite a few interesting properties compared to the properties of their bulk solid phase. One such property, the flow of fluids through them, has been engaging the attention of scientists in many disciplines. The petroleum engineers are interested in knowing the quantity and the maximum possible rate of fluid withdrawal from reservoir rocks. The soil-scientists concern themselves with the distribution and movement of soil-moisture. Chemical engineers, likewise, dealing with the problem of drying, are faced with the question of determining the rate at which the moisture from the pores can move up to the surface. Similarly while analyzing the performance of a packed bed, it is pertinent to evaluate the effectiveness of mass-transfer as well as liquid hold-up. Internal void structure is important in determining the effectiveness of batteries as well as the moisture movement capacity of the concrete and bricks.

The total internal surface area, porosity or permeability do not provide adequate information about the complex pore structure of porous media. Quite often, it is necessary not only to know these cumulative properties but also the distribution of pore sizes. The shapes of the relative permeability



and capillary pressure curves are markedly affected by pore-size distribution. Of the two, relative permeability does not seem to be suitable for determining the pore-size distribution because of the averaging effect associated with the flow phenomena in the whole spectrum of pore-sizes. Capillary pressure, on the other hand, is a unique function of pore-size, interfacial tension and wettability. Keeping the latter two quantities constant it is possible to estimate the sizes and proportions of the contributing pores from the successive higher values of capillary pressure.

Capillary phenomena comes into play whenever a fluid/fluid interface is in contact with a solid surface. Due to unequal interfacial tensions, fluid adjusts itself to attain thermodynamic equilibrium, thereby minimizing surface free energy. The well known Laplace equation which relates the various quantities affecting capillary pressure is

$$P_c = \gamma \left( \frac{1}{r_1} + \frac{1}{r_2} \right) \quad (1.1)$$

where

$P_c$  = Capillary pressure,

$\gamma$  = Interfacial tension

$r_1$  &  $r_2$  = Two principal radii of curvature of the surface at any point.

The implicit assumption that the sum of reciprocals of the two principal radii of curvature (mean curvature) is the same at every point on the equilibrium surface, is a

mathematical consequence of the fact that the surface area tends to a minimum (i.e. spherical or nearly so in most cases). All methods of pore-size determination, that make use of capillary pressure are based on the hypothesis that the mean curvature of an equilibrium liquid surface can somehow be related to the pore-size. This relationship is difficult to establish for any shapes other than that with the simplest geometry. For straight cylindrical capillaries, Laplace's equation can be written as

$$P_c = \frac{2\gamma \cos \theta}{r} \quad (1.2)$$

where  $\theta$  is the angle of contact of the interface through the wetting phase and  $r$  is the radius of the capillary. This equation can correctly predict the pore-sizes and their distribution if bundle of parallel tubes is a valid model for porous media. For real system, this is an obvious over simplification and the equation will relate the capillary pressure to the radius of the largest opening leading to the pore rather than the radius of the pore itself. But in the absence of a better known method this pore entry radius is taken as a measure of the actual pore-size. Implied in this is the assumption that the actual pore-size is some unique function of the pore entry size for pores of all sizes. This however is difficult to justify.

In capillary pressure experiment with porous media, the sample is gradually desaturated of the wetting phase by

injecting some non-wetting fluid (making known contact angle with the solid surface) at successive higher pressure. At equilibrium, the capillary pressure opposing the entry of non-wetting phase,  $P_c$ ; is balanced by the externally applied pressure. This  $P_c$  when put in Eq.(1.2) gives the radius of the smallest pore,  $r$ , invaded by the non-wetting phase. Knowing the saturation of the non-wetting phase in the sample at the stage, we arrive at the value of the fractional pore volume contained in the pores with radius greater than or equal to  $r$ . By successively increasing  $P_c$ , non-wetting phase is forced into smaller and smaller pores and the fractional pore volume corresponding to different values of  $r$  can be obtained. This method has been universally used for the calculation of volumetric pore-size distribution in porous media.

For fluid flow calculations, the pore number distribution is the desired quantity. To arrive at the number distribution from volume distribution, it is essential that we make some assumption about the pore-geometry and its dimensions. For parallel tube model of porous media, the quantity in question is the relation between the tube radius and length. Based on the assumption that  $l = Cr^x$ , where  $C$  is proportionality constant and  $r$  is radius, Fatt<sup>1</sup> derives the number distribution function as follows:

$$f(r_2-r_1) = \frac{\int_{s_1}^{s_2} P_c^{2+x} ds}{\int_0^1 P_c^{2+x} ds} \quad (1.3)$$

where  $f(r_2-r_1)$  = frequency of occurrence of pores in the  
interval  $r_2-r_1$   
 $S$  = saturation of the non-wetting phase

There is considerable disagreement between different workers in the field about the value that  $\lambda$  should assume. Whereas Fatt<sup>1</sup> proposes a value of -1. Meyer<sup>2</sup> implicitly takes this as 1. Dallavalle<sup>3</sup> seems to have some experimental results to back his suggestion of the value between 0 and 1. In the absence of a conclusive evidence, this factor still remains uncertain.

The method just discussed is essentially empirical in nature. For quantitative description of flow phenomena in porous media, a functional relation between the pore-size distribution and capillary pressure curve is needed. It will be our endeavour in the present work to examine the existing models and suggest one which can reasonably interpret the experimental  $P_c$  vs saturation curves in terms of pore-size distribution.

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## CHAPTER 2

### LITERATURE REVIEW AND ANALYSIS

Natural porous systems can be viewed as inter-connected network of voids of different shapes and sizes separated by interconnecting links or necks. Often the behaviour of such a system is approximated by a bundle of capillaries<sup>4</sup>. Dullien and Batra<sup>5</sup> have collected a comprehensive list of references of the attempts made in this direction in their review article. It is apparent that very few real porous media will contain pores of the straight cylindrical shapes, and therefore the pore radii calculated from the capillary pressure have to be considered as equivalent pore radii. This is defined as the radius of a straight cylindrical capillary that would give rise to the same capillary pressure as the measured value. Since a variety of different capillary shapes may give rise to the same capillary pressure, the pore dimensions calculated from capillary pressure measurements are at best semi-quantitative. The equation relating properties of porous media to the radius distribution of the equivalent bundle of tubes have been given by a number of authors<sup>6-9</sup>. However, apart from the mathematical simplicity associated, the most glaring weakness of the model is the prediction of highly anisotropic properties. Porous systems on the other hand are known to be isotropic in nature. In spite of its success in correlating certain properties viz. permeability,

formation factor etc., the model has failed to approximate the capillary pressure vs saturation and its hysteresis.

For more complex systems, such as random packing of non-spherical particles, Carman<sup>4</sup> suggests that twice the hydraulic radius is the suitable value of  $r$  in the following expression for  $P_c$ :

$$P_c = \frac{2 \gamma \cos \theta}{r} \quad (2.1)$$

where the hydraulic radius is defined as the ratio of porosity  $f$  to the surface area  $A$  in unit bulk volume. A more accurate account of the curvature for different geometry of the capillary is given by Gregg and Sing<sup>10</sup>. On substitution Eq.(2.1) is reduced to

$$P_c = \frac{\gamma \cos \theta A}{f} \quad (2.2)$$

Substituting the expression for the specific surface area in terms of permeability  $K$  and porosity, from the Kozeny<sup>11</sup> equation, Eq.(2.2) becomes

$$\frac{P_T}{\gamma} \left( \frac{K}{f} \right)^{\frac{1}{2}} = \left( \frac{1}{k} \right)^{\frac{1}{2}} \quad (2.3)$$

where the threshold pressure  $P_T$  has been substituted for  $P_c$ .  $k$  is an empirical textural constant of the medium and accounts for the deviation of a porous system from the model.

This was obviously a gross simplification, and Carman himself points out that, for porous bodies with widely varying pore-size distribution, calculations based on Kozeny-Carman

model can be quite wrong.

### Sphere Pack Model:

The earliest attempt in approximating the flow behaviour of porous media was their simulation by packs of uniform spheres. But the complexity of the pore-geometry in sphere-packs prevented the derivation of an accurate and meaningful description of flow behaviour through them. Recognizing the difficulty, Kozeny<sup>11</sup> inductively developed an equation relating permeability to porosity and internal surface area of a sphere-pack.

$$K = \frac{C f^3}{TS^2} \quad (2.4)$$

where  $f$  = porosity

$T$  = tortuosity

$S$  = specific surface area

Kozeny equation, as modified by Carman<sup>12</sup> and given as

$$K = \frac{f^3}{k S^2 (1-f)^2} \quad (2.5)$$

did not prove to be of much value, aside from its use in estimation of the surface area of powders.

A comprehensive review of the use of sphere-packs to model the flow behaviour of packed beds, has been given by Haughey and Beveridge<sup>13</sup>. In their analysis, the emphasis has been in arriving at the mean fractional voidage for both regular and random packing, on the basis of the position coordinates and the coordination numbers, rather than the pore -

geometry. Generally speaking, particle shape and size distribution are the two factors most likely to affect the packing structure and its properties. Some work has been carried out on the densest packing of non-spherical particles. But the multiplicity of packing types with the same coordination number and vice versa, accompanied by the size distribution of particles further complicate the pore structure. Hence the task of analytical description is rendered almost hopeless.

The problem of capillary hysteresis in uniform sphere packs was studied by Kruyer<sup>14</sup>, Frevel and Kressley<sup>15</sup>, Meyer and Stowe<sup>16,17</sup> and more recently, by Melrose<sup>18</sup>. Their analysis points out that the curvature of the invading interface of non-wetting phase is generally larger resulting in higher value of capillary pressure compared to the retracting interface associated with imbibition. This, according to them, may be the reason for the porous media exhibiting capillary hysteresis.

Naar and Wygal<sup>19</sup> view any porous media as a random mixture of spherical particles and propose a model based on the principle of averaging the properties of the basic sets to arrive at the mixture-properties. The problem essentially is finding of appropriate weighting factors to average the basic set properties, determined experimentally. Expressions for porosity, permeability and capillary pressure behaviour of the porous media have been developed. But the experimental support to this model is too meagre to be accepted.



Network Model:

The description of single and multiphase fluid flow through capillary pores in porous media has been unsatisfactory because the pore-geometry is too complex to be described adequately by analytical expression. Markin<sup>20</sup> used a model consisting of a system of randomly arranged intersecting voids with circular cross-section and continuously varying radius. No more than three branches could converge at any point in the network. This model, however, does not seem to have gained the favour of the research workers in the field.

Fatt<sup>1</sup> replaced each pore with a cylinder in his two dimensional network with different grid patterns. He could incorporate random assignment of parameters, such as pore-size distribution and number of cylinders meeting at a node point, in the model. Fluid flow in the network could be followed as one pore after another was desaturated.

All of Fatt's calculations were performed assuming a continuous wetting phase in the tubes. As a consequence, no wetting phase could be trapped in a desaturation process. Dodd and Kiel<sup>21</sup> extended this work by applying desaturation steps such that wetting fluid could be trapped. Cylindrical pores were assumed to contain only one fluid at a time; thus allowing the displaced fluid to be trapped if no continuous path to the effluent end was available. Thus at any time the pore could be either full of wetting phase or non-wetting phase.

Singhal<sup>22</sup> modified Fatt's model by providing for the possibilities of different flow regimes in different channels during desaturation process. The four basic flow regimes viz. single phase flow, displacement, annular and slug flow were allowed to occur any where in the model whenever suitable conditions existed. In addition, he substituted triangular capillaries for circular shaped tubes to account for funicular flow regime over extended range of saturation. A trapping factor, evaluated from the comparison of the model with the experimental results, was used to effect trapping of fluid. This model has duplicated the relative permeability behaviour of porous media reasonably well and we propose to use the same model for approximating its capillary pressure vs. saturation behaviour.

#### Other Model:

Haring and Greenkorn<sup>23</sup> have proposed a parametric statistical model, from the theoretical considerations, to calculate the macroscopic properties such as saturation, permeability and dispersion coefficient in porous media. Porous medium is approximated by a large number of randomly oriented straight, cylindrical pores with randomly varying radius and length. The relationship between saturation and  $P_c$  contains two constants which are the parameters of the pore-size distribution function. They maintain that the two parameter incomplete Beta function can adequately represent

most of the pore-size distributions encountered in porous media. Non-uniformity of a medium can be incorporated by adjusting the magnitude of the two parameters in the distribution function. Of all the models proposed to-date this appears to be the most promising for analytical description of flow phenomena as well as mass transfer through porous media.

Paytakes<sup>24</sup> et al, while developing a model for the packed bed, point out some in-consistency in Haring and Greenkorn's model. Whereas in Haring's model the minimum tube size is implicitly assumed as zero, the smallest pore-size in a packed bed is definitely not zero. As a consequence, the average pore diameter calculated from this model are smaller than the smallest pore calculated from sphere pack model. The calculated pore length is about equal to the half the average grain diameter of the pack. However, this minor inconsistency in the model can be removed by substituting for the finite value of the smallest pore-size for packed bed and thereby slightly modifying the model.

In their own model, Paytakes et al assume convergent-divergent circular tubes as the basic units of which a packed bed is assumed to comprise of. These basic units do not have any lateral connection thus allowing fluid flow only in the vertical direction. By introducing convergent-divergent flow channels, they seem to have accounted for inertia effects in

flow path. However, this could not be a realistic approach for porous media where interconnections **are** quite important in considering the flow behaviour.

## 2.2 Pore-Size Distribution:

It is obvious that pore-size distribution is very important in describing fluid-flow through porous media. Ritter and Drake<sup>25</sup> proposed a method of determining the pore-size distribution from mercury porosimetry data. The basis of this method is the concept that mercury is forced into gradually smaller pores against capillary forces as the pressure is increased. The fact, that such information does not directly give the pore-size distribution is obvious. However, pore-size distribution obtained from Nitrogen adsorption agrees well with that calculated from mercury porosimeter data on the assumption of parallel tube model.<sup>26</sup> Mercury porosimetry will not detect the dimensions of those pores that are accessible only through necks narrower than the pore itself. The volume of these pores of limited accessibility will be erroneously assigned the dimensions of the largest neck leading to these pores. They analyzed a number of natural substances and concluded that the pore size distribution can be represented by three parameter modified Maxwellian distribution function. Haring's two parameter distribution function is simpler and should be preferred.

Meyer<sup>2</sup> attempted to correct this distortion in the pore-size distribution due to the presence of the pores of limited accessibility. On the assumption that the pore sizes follow Poisson distribution, he calculated the probability of a pore of radius  $r_0$  not being connected to the pores of radius  $r \gg r_0$ . This probability was used to correct the mercury porosimeter values for the 'Ink-bottle' effect. The details of the derivation and the computational method is given in Appendix B.

Dulmen<sup>27</sup> proposed to determine 'two dimensional' pore-size distribution by injecting Wood's metal into the sample and using micrographic analysis. Apart from the experimental scheme, he has not published his results yet.

### 2.3 Characterization of Porous Media on the Basis of Capillary Pressure Curve:

The earliest attempt in this direction was made by Leverett<sup>28,29</sup> who put forward a semi-empirical relation

$$J(S_w) = \frac{P_c}{\gamma \cos \theta} \left( \frac{K}{F} \right)^{\frac{1}{2}} \quad (2.6)$$

where  $J(S_w)$  = capillary pressure function and is dimensionless function of wetting phase saturation on the basis of dimensional analysis. Leverett's data showed that a plot of  $J(S_w)$  vs  $S_w$  (wetting phase saturation) yielded a unique curve which described the capillary retention of wetting liquid in clean, unconsolidated sand.

Rose and Bruce<sup>30</sup> extended Kozeny-Carman treatment to relate capillary pressure with porosity, permeability and textural constant known as Kozeny constant. The expression suggested is:

$$\frac{P_T}{\gamma \cos \theta} \left(\frac{K}{F}\right)^{\frac{1}{2}} = \left(\frac{1}{K}\right)^{\frac{1}{2}} \quad (2.7)$$

where  $P_T$  = threshold pressure i.e.  $\lim_{S_w \rightarrow 1} P_c = P_T$

But these expressions, apart from classifying the porous media and in some cases predicting flow behaviour, did not give any insight in the distribution of the pore-sizes. Recently Haring and Greenkorn<sup>23</sup> have derived an expression for wetting phase saturation from  $P_c$  curve as

$$S_w = \frac{\int_0^{\frac{1}{P_c^*}} \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)}{\int_0^1 \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)} \quad (2.8)$$

where  $P_c^* = \frac{P_c}{P_T}$

$P_T$  = threshold capillary pressure

$\alpha$  &  $\beta$  = parameters of pore size distribution.

Thus in case we are able to estimate  $\alpha$  and  $\beta$  from  $P_c$  vs  $S_w$  curve, we really have an expression for pore-size distribution  $F(x)$ ,

$$F(x^*) = \frac{\int_0^{x^*} x^\alpha (1-x)^\beta dx}{\int_0^1 x^\alpha (1-x)^\beta dx} \quad (2.9)$$

where  $x^* = r/r_{\max}$ , the ratio of pore-size to the largest pore size.

This  $F(x)$  is then used to calculate the wetting fluid saturation,  $S_w$ , for any  $P_c$  by the Eq. (2.8).

#### 2.4 Plan of Attack:

From the analysis of the past work, it is obvious that the relation between the pore-structure, its distribution and the capillary characteristics of porous media is not well understood. Meyer<sup>2</sup> assumed Poisson distribution and suggested a method for applying correction for 'ink-bottle' effect. Haring and Greenkorn<sup>23</sup> suggested a statistical model for capillary pressure which could be useful in mass transfer calculations. But they approximated the pores by straight cylindrical tubes beside assuming unimodal distribution of the pores. In real porous media these are not strictly valid assumptions. In the interpretation of  $P_c$  curve for pore-size distribution, Fatt<sup>1</sup> used an arbitrary factor ( $\alpha$ ) which could take the value -1. There seems to be considerable disagreement between different workers regarding the value of this factor,  $\alpha$ . Meyer<sup>2</sup> had implicitly assumed the value 1 for  $\alpha$  in his calculation of

of probability function for the pores of limited accessibility.

To find a method which can interpret  $P_c$  curves satisfactorily, we will do the following:

a) Networks will be constructed for different pore-size distributions and by allowing them to imbibe nonwetting fluid under successively higher pressure,  $P_c$  curves will be generated for different distributions.

b) An attempt will be made to workout a procedure for interpreting  $P_c$  in terms of the pore-size distribution. To arrive at the number distribution of the pore-sizes from  $P_c$  curve, Fatt's<sup>1</sup> model with different values of  $\phi$  will be tried and the result will be compared with the actual input to the network.

c) Existence of 'ink-bottle' effect in a real porous system will be studied by the method proposed by Meyer<sup>2</sup>. The corrected pore-size distribution (volumetric) will be matched with the one estimated from the  $P_c$  curve to determine whether the effect is significant in natural system. Corrected pore-size distribution from the network  $P_c$  curve will be compared with the actual distribution to test the reliability of the approach. To this end, different expressions for characteristic volume, in Meyer's method, in terms of power to pore radius, will be tried and compared with the actual input to the network.

d) To obtain the pore-size distribution from an actual  $P_c$  curve, Haring and Greenkorn<sup>23</sup> model will be used to estimate



the parameters of distribution by non-linear least square method. Network model will be used to determine how close the estimated distribution is to the actual distribution.

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## CHAPTER 3

### MODELS USED IN THE PRESENT WORK

#### 3.1 Generation of $P_c$ Curve from Known Pore-Size Distribution:

Use of network model for generation of  $P_c$  curve consists of two steps:

a) Construction of a network simulating the porous material with a known pore-size distribution. This idea was originally suggested by Fatt<sup>1</sup> and the methodology followed here was developed by Singhal<sup>22</sup>. In the network, pores could merge at and branch out from a node point. A network of the size 6 x 8 was used in our simulation in which the nodes were arranged in square grid pattern. Thus at each node point a maximum of eight tubes could meet. Fatt<sup>31</sup> suggested, from experimental observations that each tube was connected to 10 other tubes implying that <sup>on the average</sup> 6 tubes could meet at a point. This fact was incorporated in the model by modifying the cumulative pore-size distribution obtained from capillary pressure curves, so that 25% of the tubes have zero radius. This was achieved by compressing the real distribution between 0.25 to 1.0 instead of 0.0 to 1.0 by the following expression:

$$l' = 0.75l + 0.25$$

where

$l'$  = new value of the distribution

$l$  = original value

Whereas the tube radius and location were assigned in random manner by Monte-Carlo technique, the tube length could assume only two values viz. equal to the side length of the square or its diagonal length. The grid length was arbitrarily chosen. The list of the input to a typical network simulation program is given in the Table 1. The details of simulation has been discussed by Singhal<sup>22</sup> and for the sake of completion, the relevant points are included in the Appendix A.

b) Generation of Capillary Pressure Curve: Capillary pressure characteristics of the network is evaluated by modifying and adapting the computer program written by Singhal<sup>22</sup>. Some additional checks have been introduced in the program to verify that material balance for each fluid as well as for the total fluid is satisfied at each stage of computational cycle.

Initially the network is assumed to be full of wetting fluid and is allowed to be displaced by non-wetting fluid. A fixed pressure drop ( $\Delta P$ ) is applied across the network and it is allowed to desaturate the wetting fluid in a quasi-static manner. This process continues till outflow from the network in a particular time step is negligibly small; implying equilibrium fluid distribution in the model. Theoretically in a quasi-static process the time step should be as small as possible. But this would mean larger computation time. Hence we used the time steps of the order of 200  $\mu$ sec. initially and later increased it as the desaturation process proceeded.

Instead of waiting indefinitely for zero outflow<sup>to occur</sup> in a time interval, we cut short the calculation for a  $\Delta P$  whenever the outflow in a time step is less than or equal to 1% of the outflow in the first time step. The saturation of the wetting phase in the model is then calculated thus obtaining one point on the  $P_c$  vs  $S_w$  curve. Pressure drop ( $\Delta P$ ) across the model is then successively increased and in each case the equilibrium wetting phase saturation is obtained. In this way the whole  $P_c$  vs  $S_w$  curve can be obtained over any range of pressure and saturation.

Singhal<sup>22</sup> used a trapping factor ( $0.2/\sqrt{\mu_o/\mu_w}$ ), where  $\mu_o$  and  $\mu_w$  are the viscosities of non-wetting and wetting fluid respectively, to trap the fluids in the pores during desaturation. This was merely a correction factor to match the model behaviour with actual samples. In static process like capillary desaturation, the viscosity of the fluid is not of any significance as far as equilibrium saturation is concerned. Equilibrium saturation of the wetting fluid depends solely on the curvature of the remaining fluid interfaces in various tubes. In our simulation of the network the tubes have assumed the size equivalent to the volumetric average radius of the pores. In real porous systems (granular) the pores are convergent-divergent in shape. As a result the neck radius in any tube is definitely smaller than the volumetric average radius. As the capillary pressure of any tube is determined

by the size of the narrowest constriction in the tube, the actual capillary pressure will always be larger than that calculated from the average radius.

In the present work, the trapping factor is the ratio of the volumetric average pore radius to the neck radius for each tube, thus implicitly simulating the convergent - divergent shape of the pore channels. At every stage the pore-entry capillary pressure is modified by this factor to calculate  $P_T$  at the neck. This pressure is then used to determine whether the interface will move through the pore or will be blocked.

### 3.2 Correction for "Ink-Bottle" Effect:

In natural porous systems pores are surrounded by smaller pores; recognized as "ink-bottle" effect by Meyer<sup>2</sup>. This results in assigning larger volume to the smaller pores while the volumetric share of larger pores is less than the actual volume. Evidently the use of bundle of tubes model to calculate pore size distribution is likely to be erroneous. Meyer<sup>2</sup> attempted to correct the measured data for this effect by calculating the probability of a larger pore not being connected through equal or larger pores to the mercury source in mercury porosimetry. He assumed that pore-sizes are randomly distributed and follow Poisson's distribution. In deriving the probability  $\int_0^{\infty} (r_0, r) dr$ , he overlooks the fact that the pores are mutually exclusive and asserts that this will not introduce any serious error in calculation since only

the 'zero' term in Poisson's distribution is used for calculation. Also, assumed randomness of pore sizes exclude from consideration clusters of very large or very small pores such as fractured or vuggy system.

Other simplifying assumptions made by Meyer are:

(i) that the centre of an  $r$  pore lying in volume  $v(r_0, r)$  will ensure its being connected to an  $r_0$  pore, (ii) that only those pores which are isolated from all equal or larger pores will fail to fill and (iii) volume of a pore may be expressed as  $Kr^3$  where  $K$  is a constant.

The first assumption is valid for spherical pores and seems intuitively sound for others. The implication of the second assumption is that isolated groups of mutually connected pores are not being considered. This, of course, is a serious simplification but necessary for handling the difficult subject of aggregates in a random distribution. It is hoped that the correction applied for individual isolated pores is the major correction needed. The third assumption implies that larger pores have larger length associated with them. This sounds reasonable as the larger pores are associated with larger grains for uniform packing. This assumption has one snag that  $K$  is not a constant. However,  $K$  as a constant appears only under the integral sign and cancels out. The assumption, in fact, is not that  $K$  is a constant but that its mean value in one integral is equal to that in the other.

Hence, he proposed that measured pore-size distribution should be corrected by this method to obtain actual distribution for granular porous system. Details of the method is given in Appendix B.

Computer program, written for this scheme, is given in Appendix D.

### 3.3 Haring and Greenkorn Model:

Haring and Greenkorn<sup>23</sup> have suggested the use of two parameter incomplete Beta function as the universal distribution function for the pore-size in a porous body. It was claimed by them, and rightly so, that almost any unimodal distribution, whether symmetric or skew, could be approximated very closely by the adjustment of the two parameters. Normal distribution of the pore-size was not favoured for the following two reasons:

- i) the distribution is symmetrical.
- ii) the independent variable varies from  $-\infty$  to  $+\infty$  ;  
none of which is strictly true for a porous media.

One more implicit assumption in their approximation is that the ratio of minimum to maximum pore size is zero, which is not always true. That seems to be the reason, why for a granular pack the average pore size computed on the basis of this distribution function comes to even less than the minimum pore-size computed from geometrical considerations of granular packing. Also, the average pore length is calculated to be equal to half the average particle diameter; while ideally

it should be equal. This fact has been pointed out by Paytakes, Tien and Turian<sup>24</sup>. However, this inconsistency may be overcome by slightly modifying the distribution function to:

$$g(r^*) = \frac{\int_0^{r^*} (x-x_m)^\alpha (1-x)^\beta dx}{\int_0^1 (x-x_m)^\alpha (1-x)^\beta dx} \quad (3.1)$$

where  $r^*$  = dimensionless radius of the pore. The ratio of pore radius to the largest pore radius.  
 $x_m$  = The ratio of smallest to the largest pore radii

$\alpha, \beta$  = Parameters of distribution.

Based on the assumption that the actual pore-size distribution can be approximated reasonably by incomplete Beta function, Haring<sup>23</sup> et al arrived at the following expressions for the wetting fluid saturation,  $S_w$ :

$$S_w = \int_0^{\frac{1}{P_c^*}} \frac{(\alpha+\beta+3)!}{(\alpha+2)! \beta!} x^{\alpha+2} (1-x)^\beta dx \quad (3.2)$$

$$= B\left(\frac{1}{P_c^*}; \alpha+2, \beta\right) \quad (3.3)$$

where  $B\left(\frac{1}{P_c^*}; \alpha+2, \beta\right)$  is incomplete Beta function with  $\alpha+2$  and  $\beta$  as parameters.

$P_c^*$  Dimensionless capillary pressure,  $P_c/P_T$

$P_T$  Threshold capillary pressure i.e.  $P_c$  when

$S_w \rightarrow 1$ .



In this work we shall try to fit the Eq.(3.3) by non-linear least square method. Standard IBM program SDA-3094 will be used for this purpose.

\*\*\*\*

## CHAPTER 4

### RESULTS AND DISCUSSION

As already mentioned in earlier chapters network seems to be a good model for predicting the flow behaviour of porous media. Apart from its closer and better physical similarity with porous media, capillary pressure curves obtained from it look quite realistic. However, there may be some weaknesses in this model which will be discussed later in this chapter.

Capillary pressure ( $P_c$ ) vs wetting fluid saturation ( $S_w$ ) from the networks are given in Figs. 2a to 2f. Each network was generated from a specified pore-size distribution, which was assumed to represent a hypothetical porous medium. Pore-size distribution used to generate networks were; arbitrary distribution, Beta distribution and Poisson distribution. Besides, a couple of bimodal arbitrary distributions were also used. The networks with bimodal distribution were used to find out if the  $P_c$  curve could give some indication of the multimodality in the distribution. In each case, except the first network, the largest pore-size used was  $20\mu$ . The input distribution was compressed in each case between 0.25 to 1.0 to accommodate Fatt's Beta factor as suggested by Singhal<sup>22</sup>.

In spite of the very distinct and extreme forms of the distributions used to generate the networks, the calculated

$P_c$  curves were not significantly different from each other. Thus giving the impression that capillary pressure is not a very strong function of the pore-size distribution in the network. Also threshold pressures ( $P_T$ ) obtained from the network  $P_c$  curves (corresponding to  $S_w = 1.0$ ) do not always agree with that predicted from the bundle of tubes model. Threshold pressure, from the definition, depends on the size of the largest tube in the input face of the network. But, in view of the fact that tubes are assigned randomly at different node points, it is possible that the largest size tube may not occur at the input face. In that case  $P_T$  predicted from the bundle of tubes model will be different from that evaluated from the network. From the inspection of Fig. 1.e, it is obvious that the largest tube size (20  $\mu$ ) does not appear in the input face and hence the calculated  $P_T$  from the network is higher than that predicted for 20  $\mu$  tube radius (0.259 psi). Also, during the computation of  $P_c$  curve from networks, more than one fluid/fluid interfaces were observed in a continuous flow channel. This factor has not been accounted for in the bundle of tubes model and can be one of the reasons resulting in the difference in the two values of  $P_T$ .

Other features of the network likely to have influenced the  $P_c$  curves are; (i) number of tubes (ii) ratio of the tube length to the radius (iii) the extent of inter-connection between the tubes and (iv) existence of different flow regimes

in flow channels.

(i) Fatt<sup>31</sup> estimated number of pores in a 1/2" cube sample of sandstone to be of the order of 10,000. In our networks, the number of tubes varied between 89 to 101. Whether such a small number of tubes (pores) could reasonably approximate the flow behaviour of real porous media with huge number of pores, is open to doubt. With such a small number of tubes, it is the relative position of the tubes which matters more than the size distribution. If the investigation could be repeated with larger sizes of networks (500 to 1000 tubes), the result may throw some light over this question. Our limitation in computer memory and time prevented us from trying bigger networks. Fatt<sup>1</sup> asserts that tubes more than 200 in number do not substantially affect the nature of  $P_c$  curves from networks. However, he did not compare any experimental  $P_c$  curve with that of a network to prove his point that tube number is not a critical factor.

(ii) The second factor, which seems significant, is the ratio of the pore length to the pore radius. In our networks, this ratio varies from about 6 to 60 depending on the size and the location of the tubes relative to the grid. Earlier investigators suggest that the length of a pore varies according to some power of  $r$ . This factor varies between 0 and 1, according to Dallavalle<sup>3</sup>. Fatt<sup>1</sup> puts this value at -1. In one of our calculations grid size was reduced to about 1/5th

of the original value thus reducing the maximum value of length to the radius ratio from 60 to 12. The two  $P_c$  curves (Fig. 1h) are not significantly different. Further investigation with different values of the grid-size is desirable before drawing any conclusion.

(iii) The third factor to be considered is the Beta factor suggested by Fatt<sup>1</sup> and used by Singhal<sup>22</sup> in his simulation of networks. This factor essentially represents the extent of interconnection between the pores in porous media. Applied to networks, this implies average number of tubes meeting at a node point. Fatt<sup>32</sup>, from his experimental observations, points out that in a sandstone rock each pore is connected to 10 other pores thereby implying that on the average 6 tubes should meet at a node point. In Fig. 2h the three  $P_c$  curves have been obtained with different values of the Beta factor. It is obvious that the two  $P_c$  curves, for Beta factors 6 & 8, are not very different from each other, the  $P_c$  curve for Beta factor equal to 4 is significantly different from the other two. Hence it may be inferred that the extent of interconnection in a network, represented by Beta factor, is quite important and is likely to be different for different media. In our simulation this factor has been taken equal to 6.

(iv) There is experimental evidence to support the existence of different flow regimes in flow paths of physical models of porous media where one fluid displaces the other. In such systems, the interplay of viscous and capillary forces comes into existence and the flow regimes depend on  $\Delta P$  and flow

rate. This phenomenon is accounted for in the network but not in the bundle of tubes model. This could be another weakness of the bundle of tubes model. However, for mercury-vacuum system this situation, of different flow regimes in flow paths, is not likely to occur.

Simulated networks used for generation of  $P_c$  curves were tested for ~~goodness of fit~~ by  $\chi^2$  test. The pore-size distributions of the simulated networks were not found to be similar to the input distributions within a reasonable confidence limit. We suspect that the scheme of pseudo random numbers used in the simulation might not have been truly random. Consequently it was decided to use the actual distributions of the networks rather than the input distributions which they were supposed to represent. Any further work in this direction should ensure that the simulated network does pass  $\chi^2$  test to represent the input distribution. However, the weaknesses mentioned above may not be very serious in view of the results obtained from the network model.

Since our networks have discrete pore-sizes, ideally some step type  $P_c$  curves would have been expected. But from the limited number of the points on the  $P_c$  vs  $S_w$  plot, a smooth curve could be drawn. It appears that the pore-sizes may not be the exclusive factor determining the value of capillary pressure in a porous medium. Other factors like connectivity etc might also be important.

The idea of relating  $P_c$  to the size of the pores has its root in the bundle of tubes model of porous media. Even the model proposed by Haring and Greenkorn<sup>23</sup> are the modification of the same model, providing random orientation of the tubes and consequent inter-connections. Therefore to correct for inter-connection between the pores, some modification is called for in the interpretation of  $P_c$  curves based on this model.

The effect of "ink-bottle" phenomena seems to be significant in the networks, resulting in the cumulative pore-size distribution (volumetric) obtained from  $P_c$  curves, being quite different from the actual distributions. Actual distributions were computed by counting the number of tubes of different size and calculating their volumes. The difference in the two distributions can be clearly seen in the Fig. 3a to 3f. Attempts were made to correct the distributions (obtained from  $P_c$  curves) by Meyer's method<sup>2</sup> for "ink-bottle" effect. In using this method, slight modification was made in the scheme given in the Appendix B. As is obvious, in a network, tube lengths are independent of radius. As a result the pore volume as well as the characteristic volume defined in Meyer's method becomes proportional to the radius squared rather than radius cubed. The corrected distributions (volumetric) is compared with the actual and that obtained from  $P_c$  curves in Figs. 3a to 3f.

Effect of the pores of limited accessibility ("ink-bottle" effect) on the volumetric distribution appears quite-pronounced in some of the natural substances investigated by us. The substances included porous plate, fritted glass, pelleted gel etc. Meyer's method as given in the Appendix B was used for these calculations and the result is given in Fig. 4a to 4d.  $P_c$  data for these substances were obtained from Ritter and Drake<sup>25</sup> and are reproduced in the Table 3. The same method was applied to  $P_c$  data of some sandstone samples obtained from literature but no appreciable difference in the experimental and corrected distributions was observed; implying that this phenomenon is not very significant in those samples. In an attempt to closely approximate the actual pore-size distribution, the exponent of  $r$  in Meyer's method was given a number of values (3 to 1.5). The curves with the exponent equal to 1.5 were observed to be better than others in approximating the actual curves (Figs. 5a to 5f). Physically this means that the pore length is  $\propto r^{-0.5}$ . This distortion from the expected relation of  $l \propto r^0$  may be due to a number of factors, like some bias in our networks, and to a greater degree on the extent of inter connection between the pores.

Attempts were also made to estimate number pore-size distribution from  $P_c$  vs  $S_w$  curves obtained from the networks. In the absence of an analytical expression incorporating network concept of porous media, investigations were carried out



to find out if Fatt's model, of bundle of tubes, could be useful. In that model (Eq. 1.3) Fatt<sup>1</sup> used an exponent  $\alpha$  which related the pore length to the radius. The same equation, with the different values of  $\alpha$ , was used to calculate pore-size distributions (number) from  $P_c$  curves of the networks. It is apparent from Figs. 5a to 5f that for the values of  $\alpha$  lying between -2.5 to -3.5 (mostly -3.0) the calculated distributions are reasonably close to the actual distribution. The physical implication of this value is that the pore length ( $l$ )  $\propto r^{-3.0}$ . In our networks the tube lengths were independent of the radius. But because of the fact that we have distinctly two groups of lengths, side lengths and diagonals of the grid, in our networks, pore lengths could not be said entirely independent of the radius. Also, the small sample size, extent of interconnections and the non-randomness of the pseudo random numbers used in simulation, might have introduced some fictitious relation between  $l$  and  $r$ .

Haring and Greenkorn<sup>23</sup> model relating pore-size distribution (number) to capillary pressure and saturation, was tested by estimating the parameters of the distribution from  $P_c$  vs  $S_w$  curves by non-linear least square technique. These parameters were put back in incomplete Beta distribution function to calculate the number distribution. These calculated pore-size distributions did not match the actual distribution obtained by counting the number of the tubes from the networks.

One of the curves fitted to the network  $P_c$  curve is given in Fig. 6.

From the limited number of analysis performed by us, it is doubtful whether this model could at all relate the pore-size distributions to  $P_c$  curves of real porous media.

From our study it can be said that networks could be used as a valid model of porous media and pore-size distributions could be obtained from  $P_c$  vs  $S_w$  curves.

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## CHAPTER 5

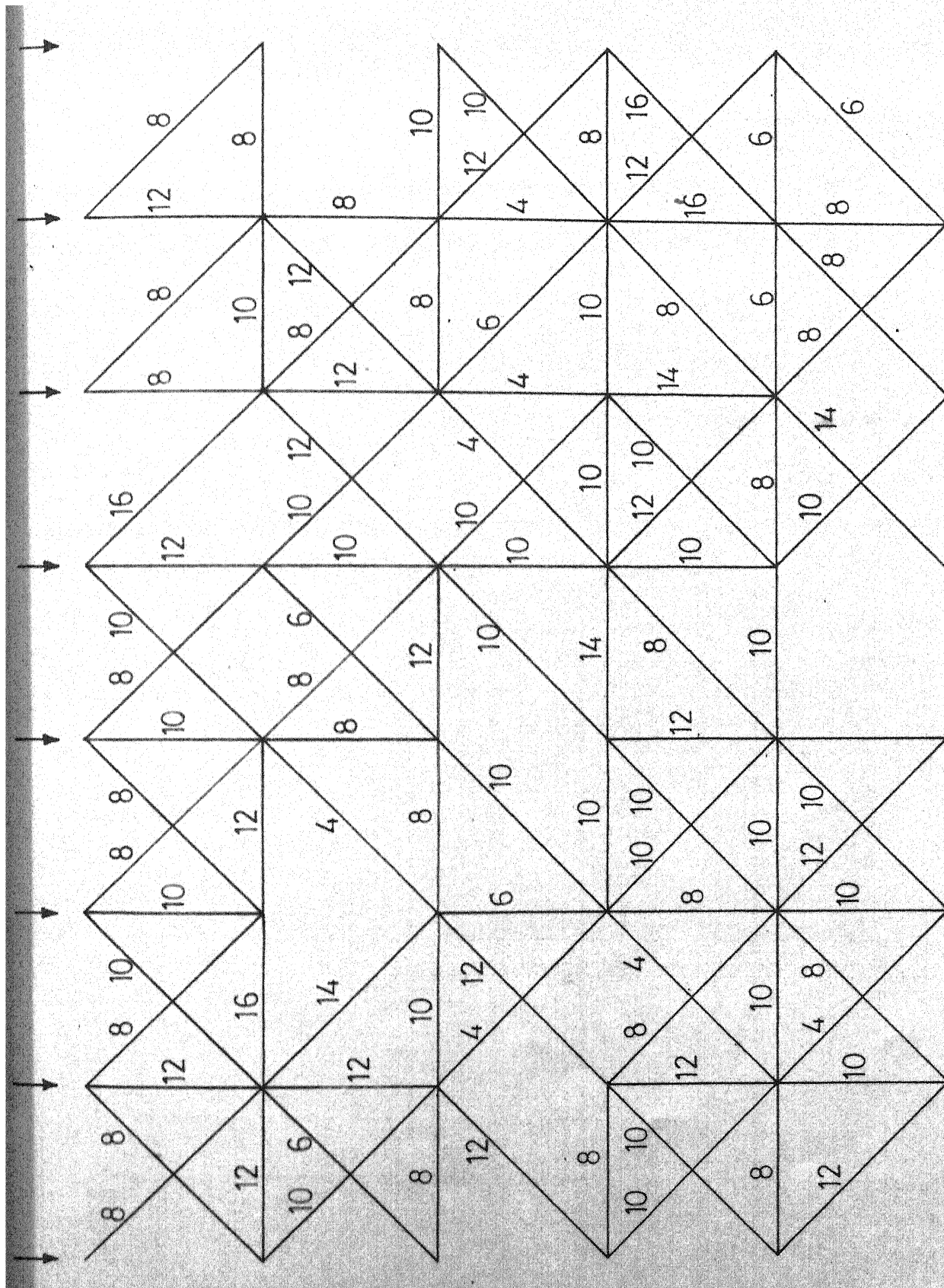
### CONCLUSIONS AND RECOMMENDATION

The classical model (bundle of tubes) of porous media have a number of weaknesses. As a result the interpretation of  $P_c$  curve based on this model is likely to be erroneous. Network is a better physical model of the porous media and  $P_c$  curves obtained from it is quite realistic. True pore-size distributions (volumetric and number) can be better estimated from  $P_c$  curves by modified Meyer's and modified Fatt's method indicated in this work.

Future work in this direction should ensure that the actual pore size distribution (number) of the simulated networks reasonably match the input distribution. More work is needed to find out the effect of tube length-radius ratio, the extent of interconnection, and number of tubes in the network on the  $P_c$  curve generated. Experimental work with physical networks are necessary to verify these theoretical findings.

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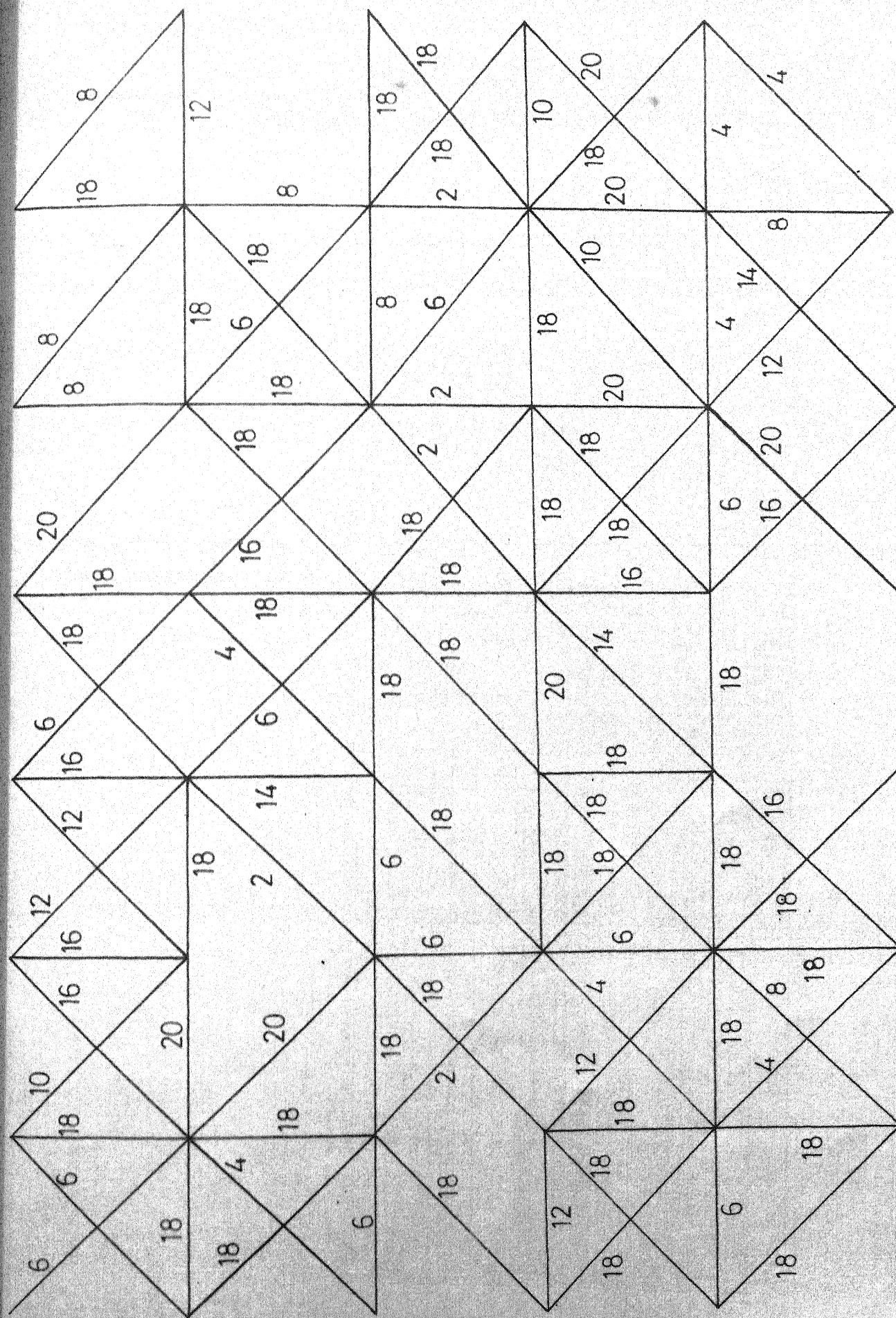


Fig. 1c - Network from arbitrary bimodal distribution. Table 2.

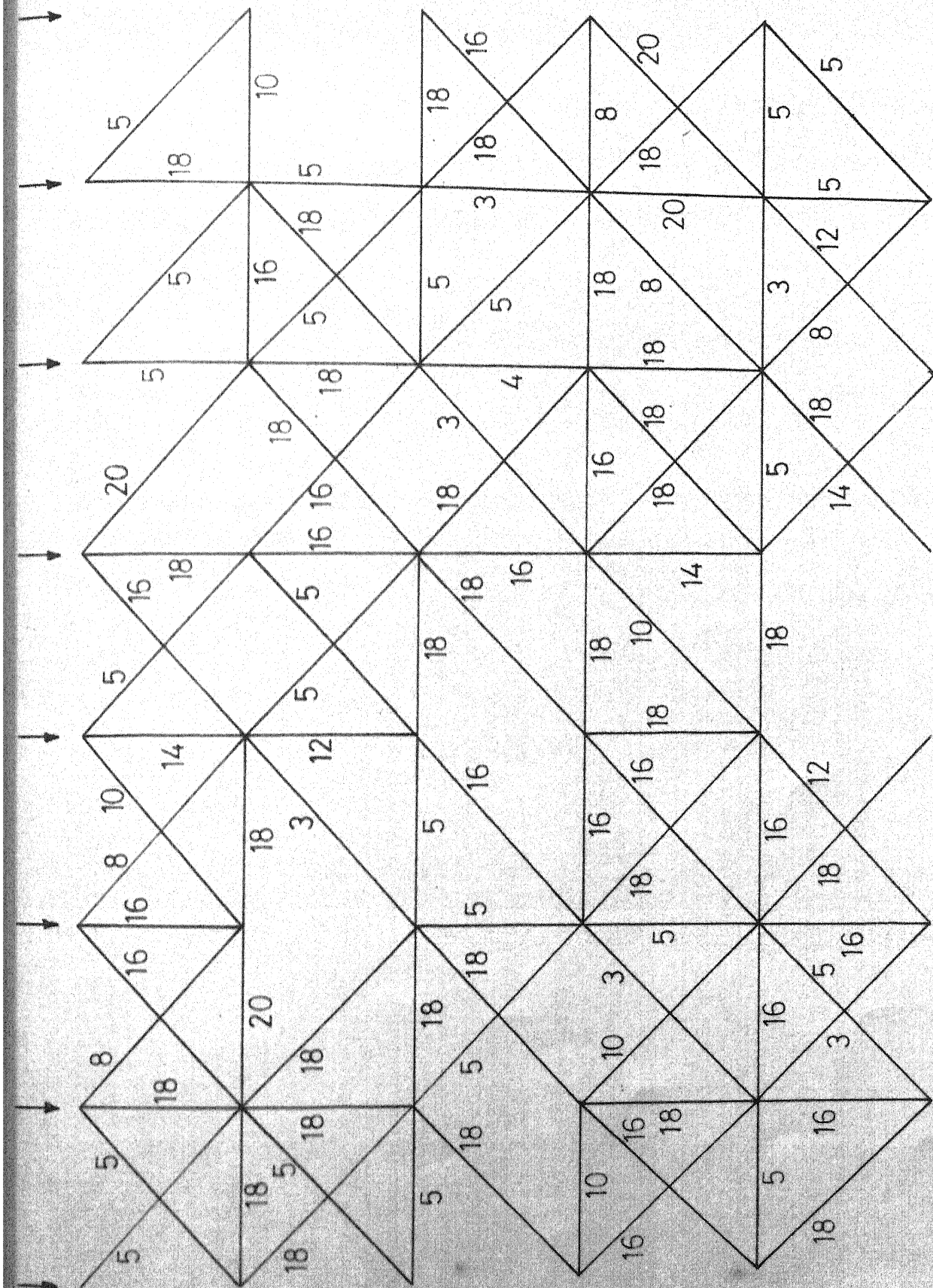


Fig 1 d - Network from arbitrary bimodal distribution. Table 2.

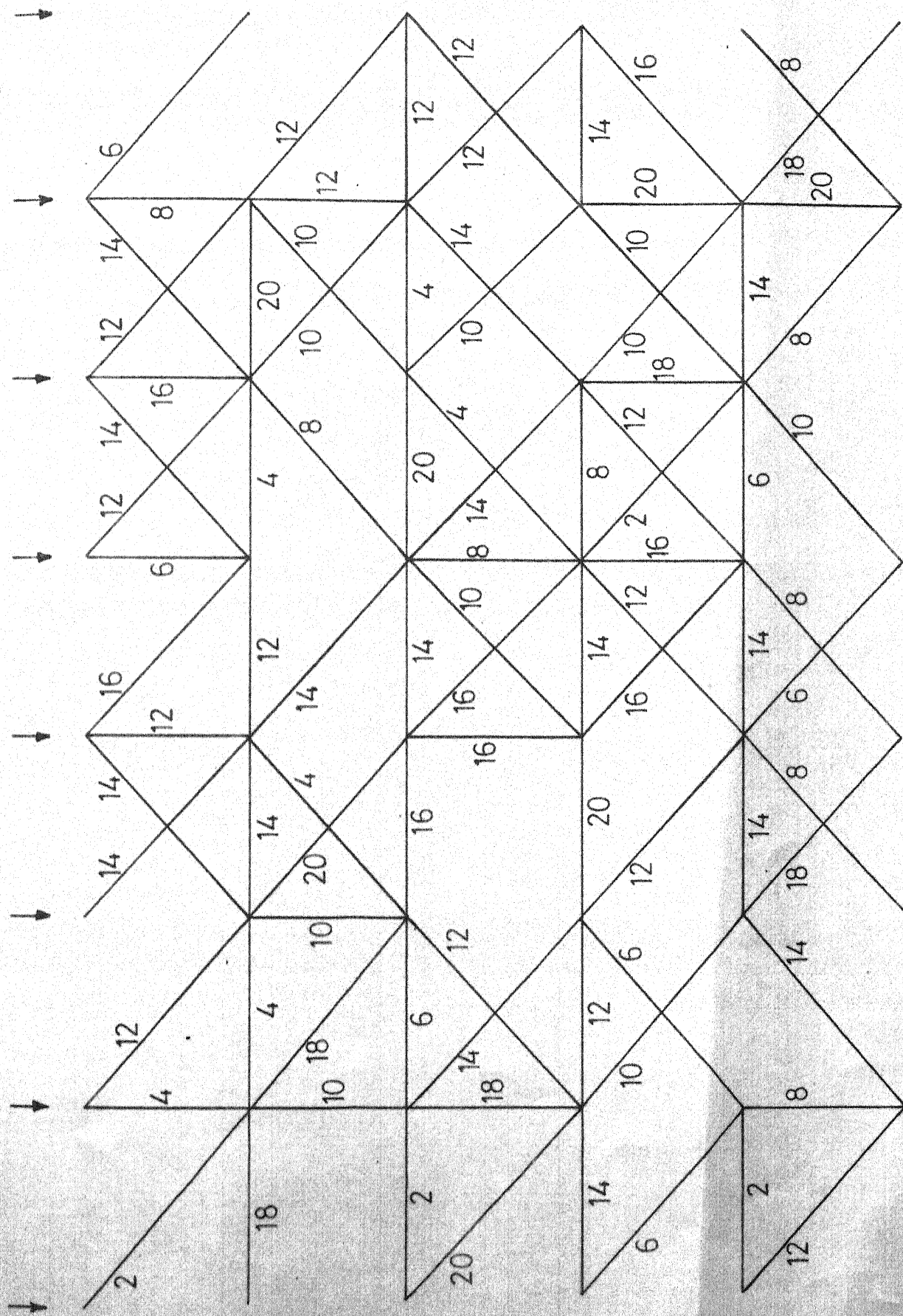


Fig.1e - Network used to obtain  $P_c$  vs.  $S_w$  curve (Fig.2e) indicating absence of the largest size tubes in the input end. Input incomplete beta distribution with parameters 1.0,1.0: Numbers indicate tube radius in micron.





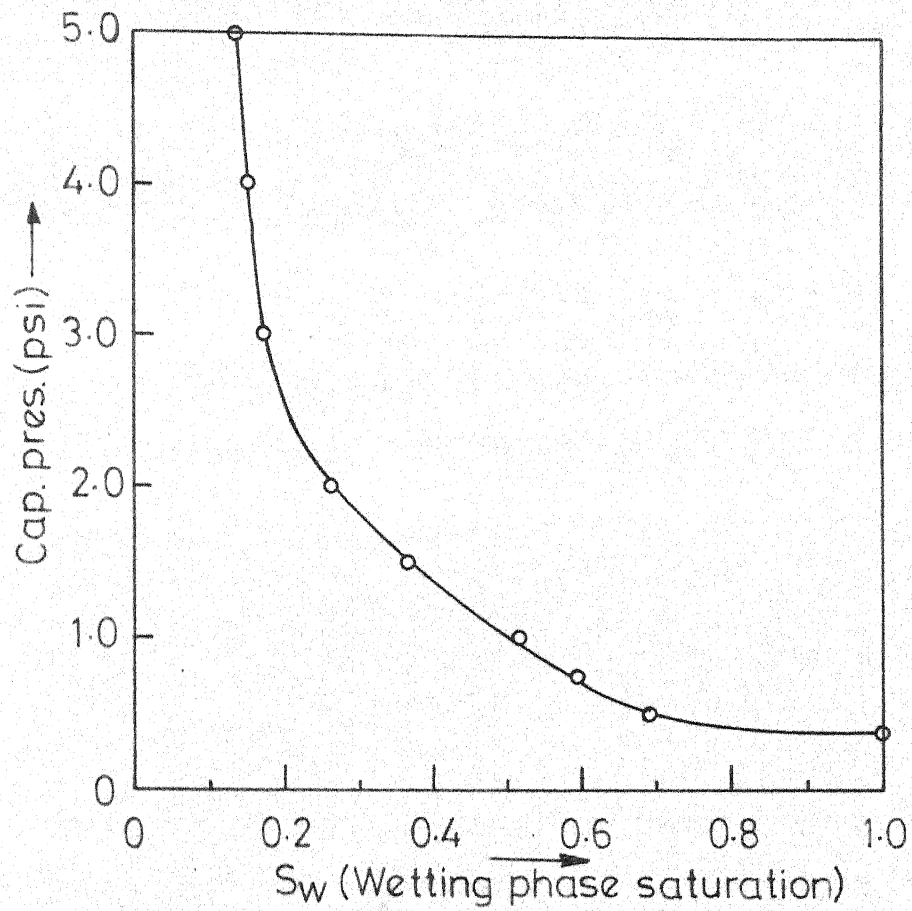


Fig.2a- $P_c$  vs.  $S_w$  curve obtained from network I Fig.1a.

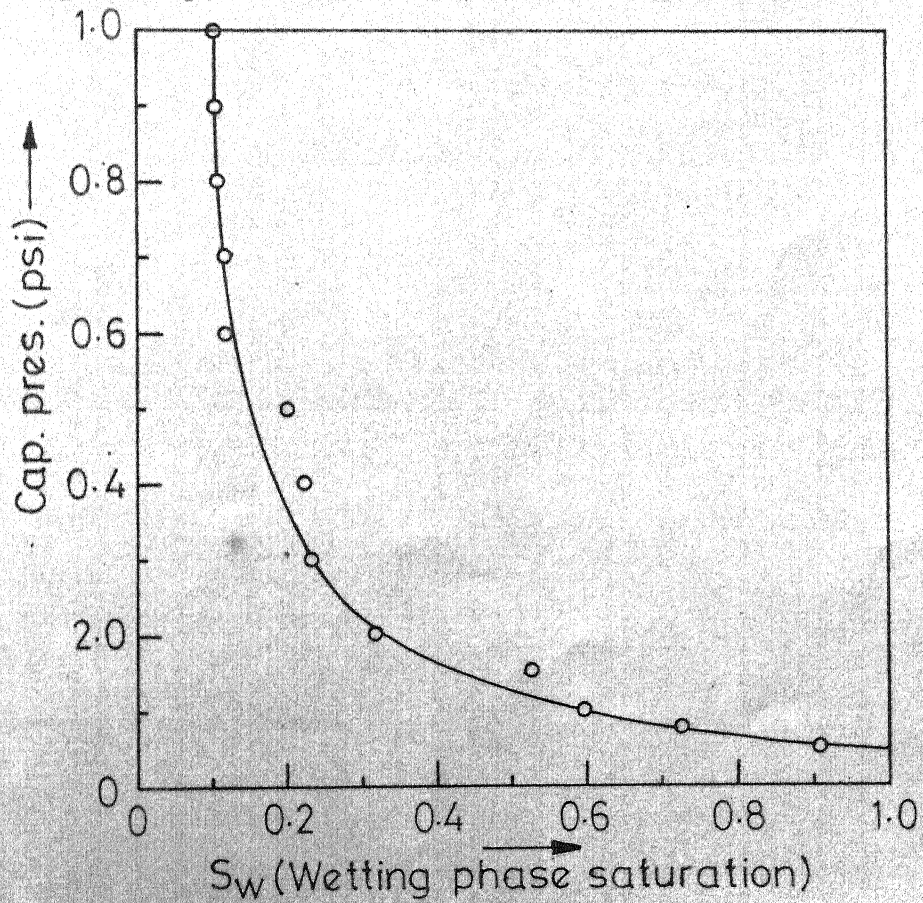


Fig.2b- $P_c$  vs.  $S_w$  curve obtained from network II Fig.1b.

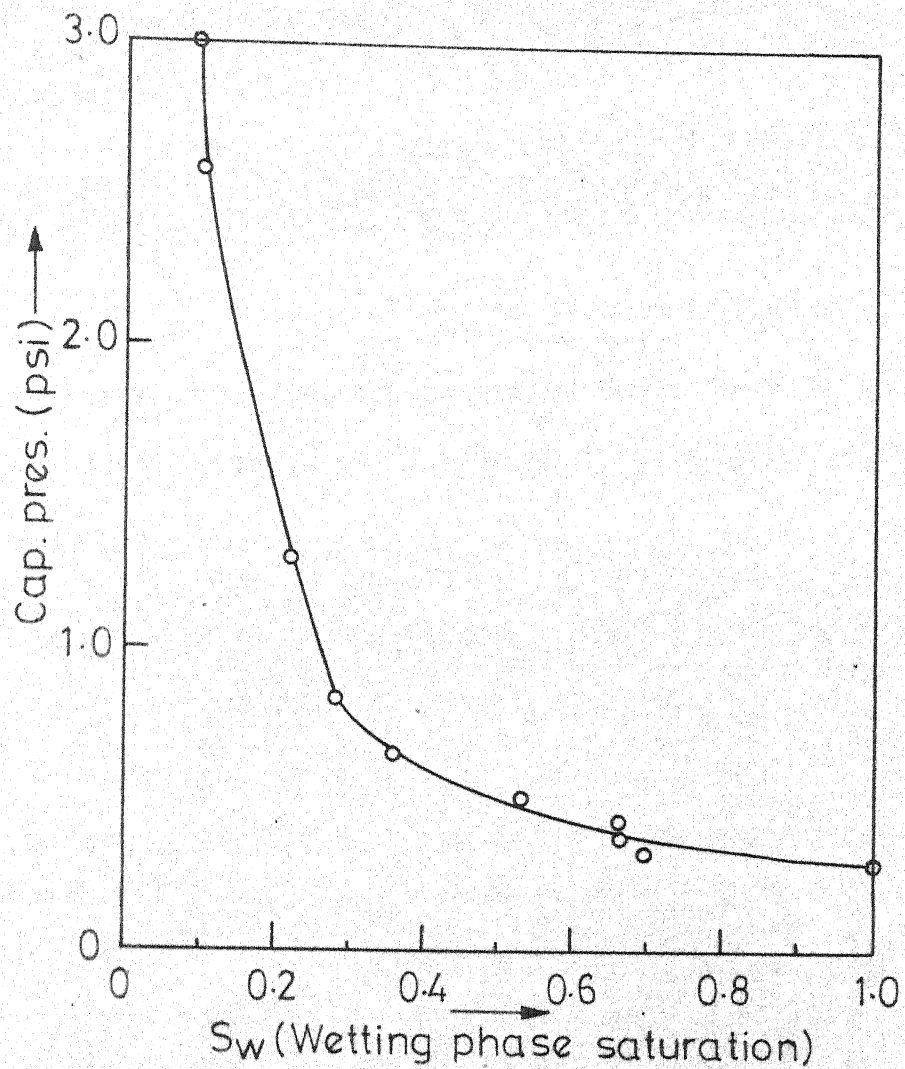


Fig.2c- $P_c$  vs  $S_w$  curve for network III Fig.1c.

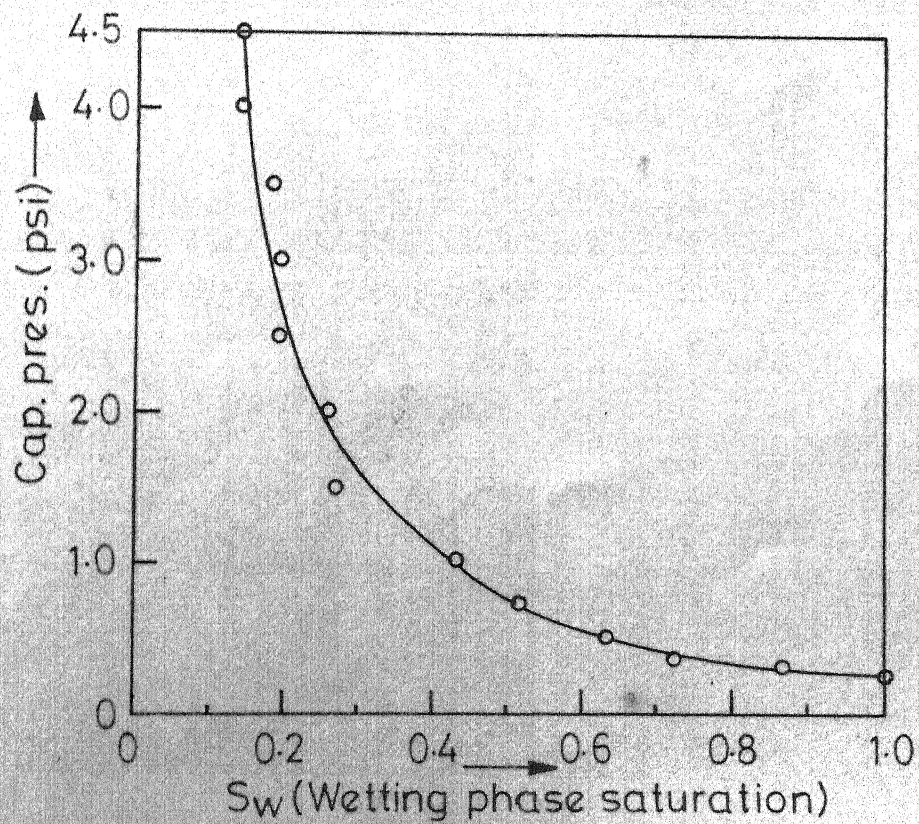


Fig.2d- $P_c$  vs.  $S_w$  curve for network IV Fig.1d.



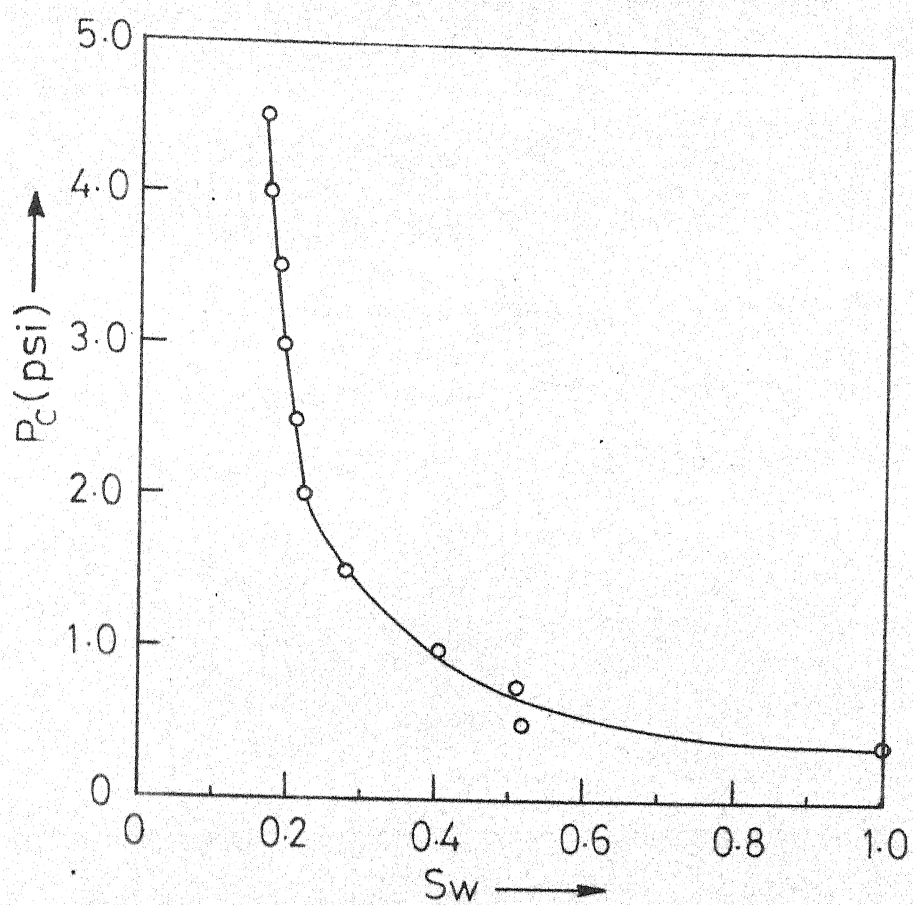


Fig.2e -  $P_c$  vs.  $S_w$  curve for network V Fig.1e.

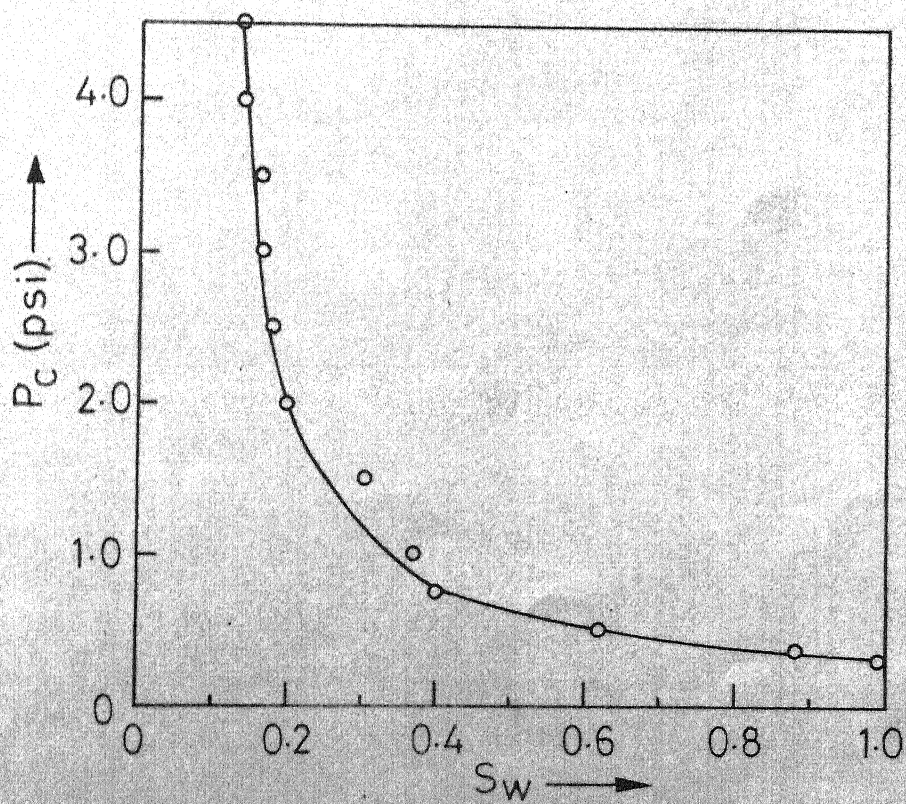


Fig.2f -  $P_c$  vs.  $S_w$  curve for network VI Fig.1f.

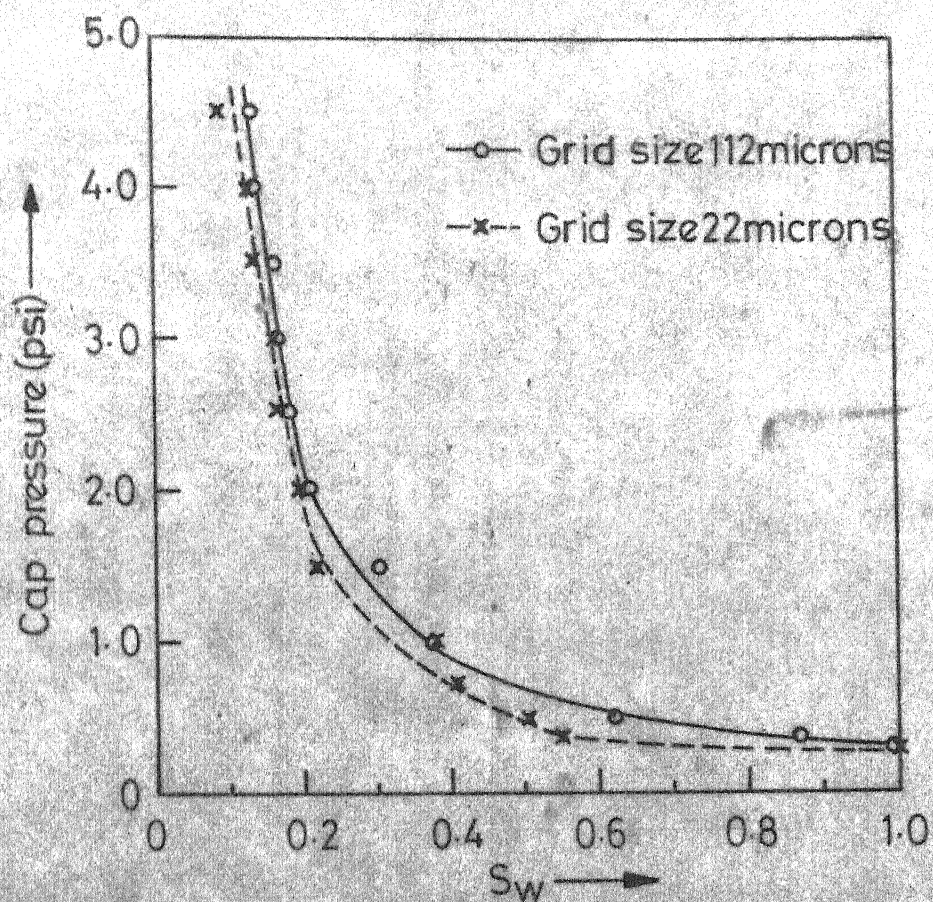


Fig. 2g - Effect of grid size on  $P_c$  curve. Network VI.

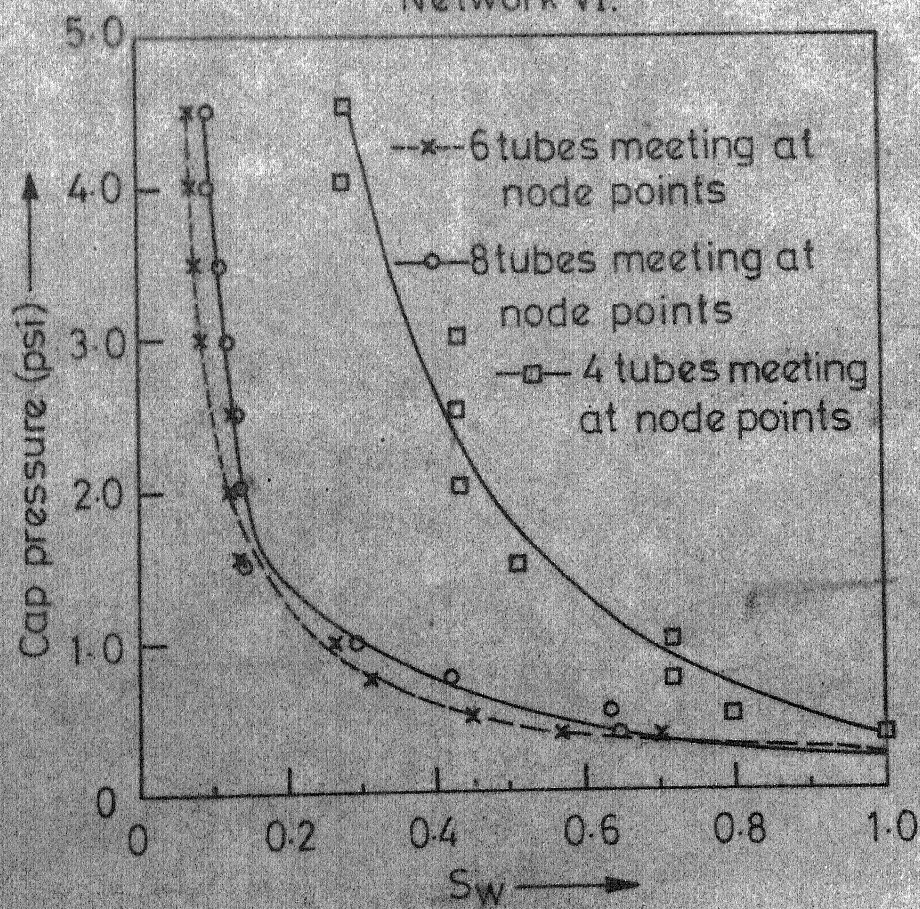


Fig. 2h - Effect of network inter connections of  $P_c$  curve. Network VI.



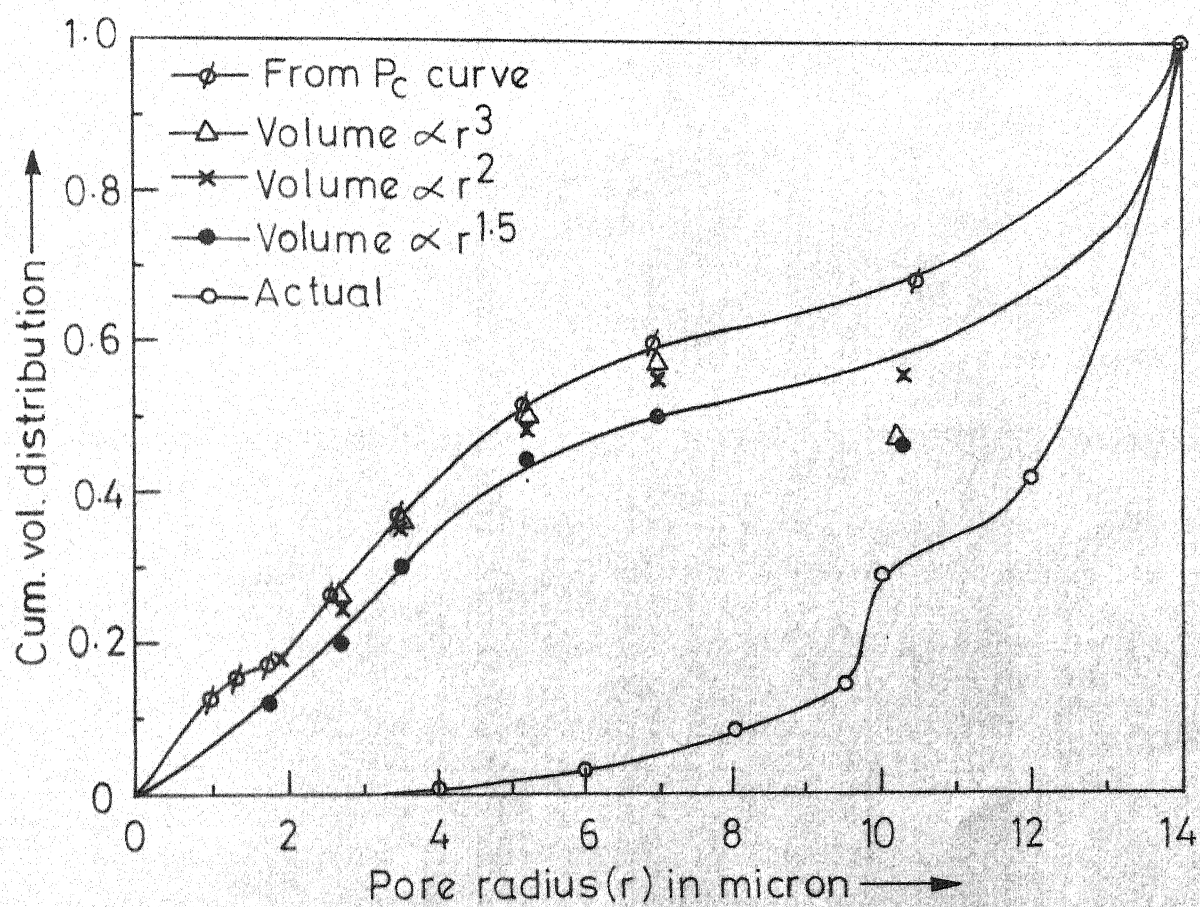


Fig.3a - Correction in volumetric distribution by Meyer's method. Network I.

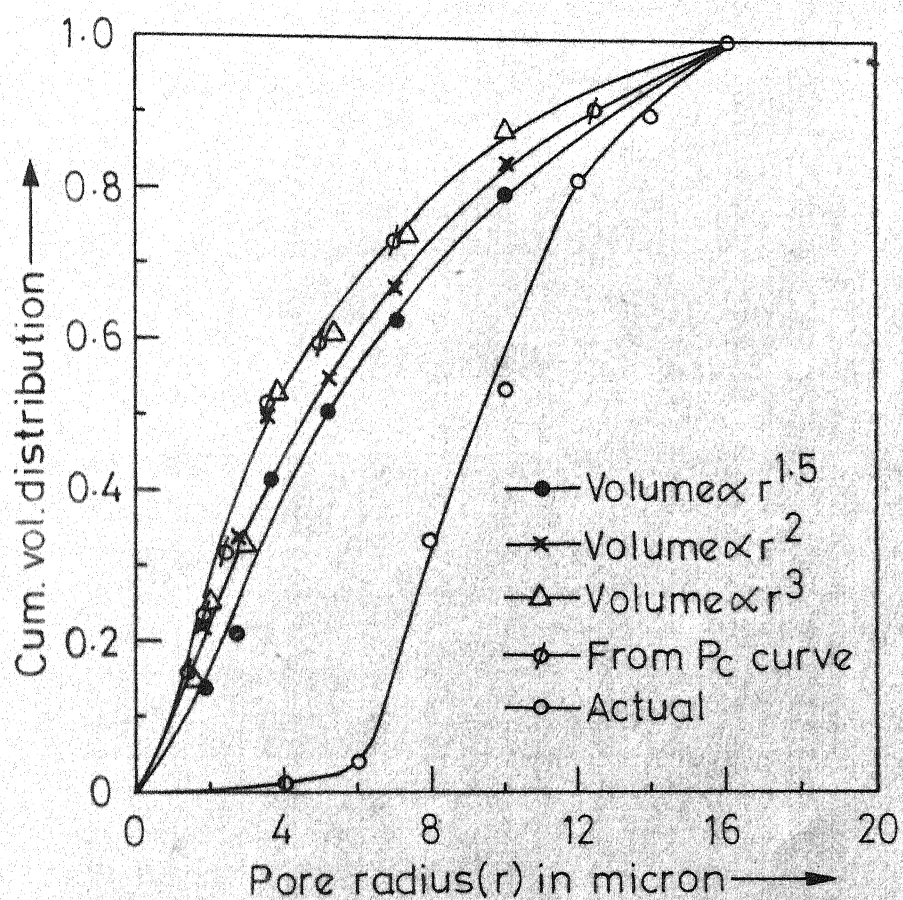


Fig.3b- Correction in volumetric distribution by Meyer's method. Network II.

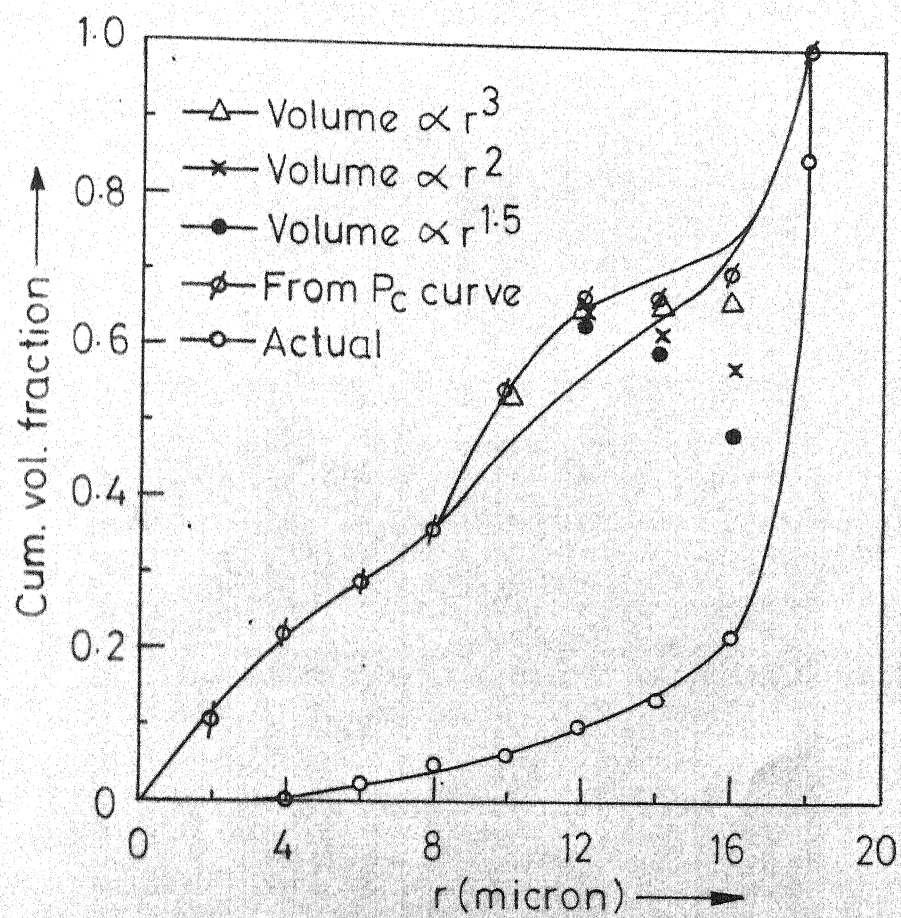


Fig. 3c - Correction in volumetric distribution by Meyer's method. Network III.



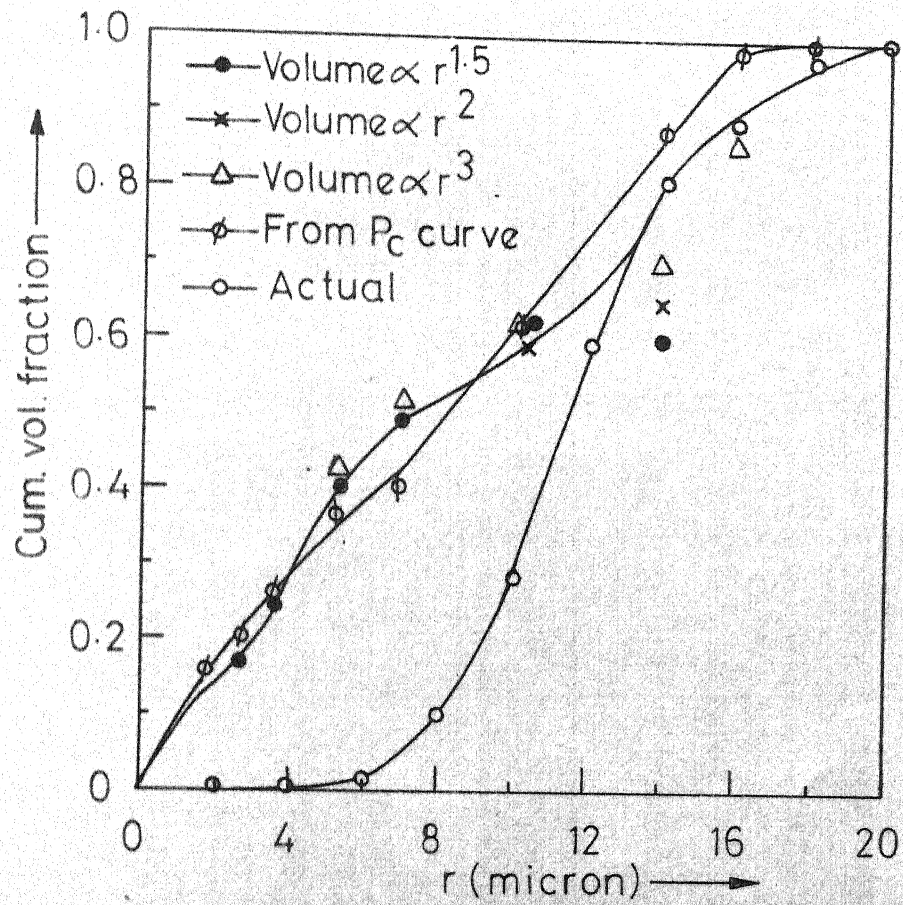


Fig. 3d - Correction in volumetric distribution by Meyer's method. Network IV.

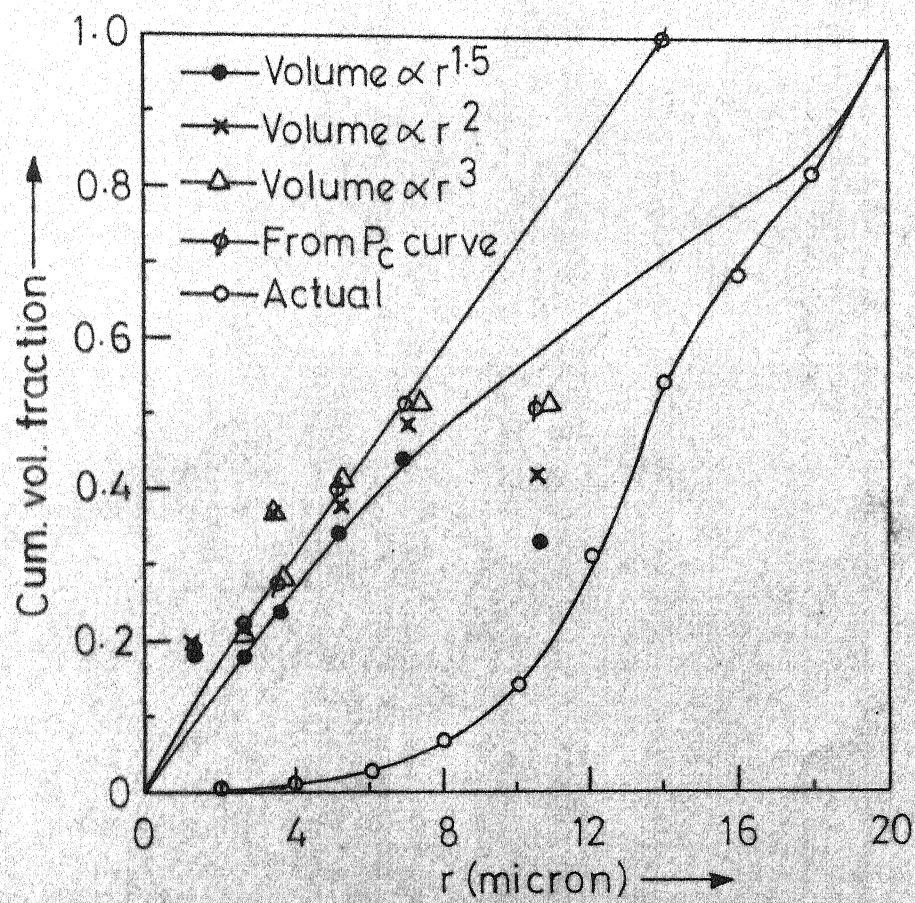


Fig. 3e-Correction in volumetric distribution by Meyer's method. Network V.

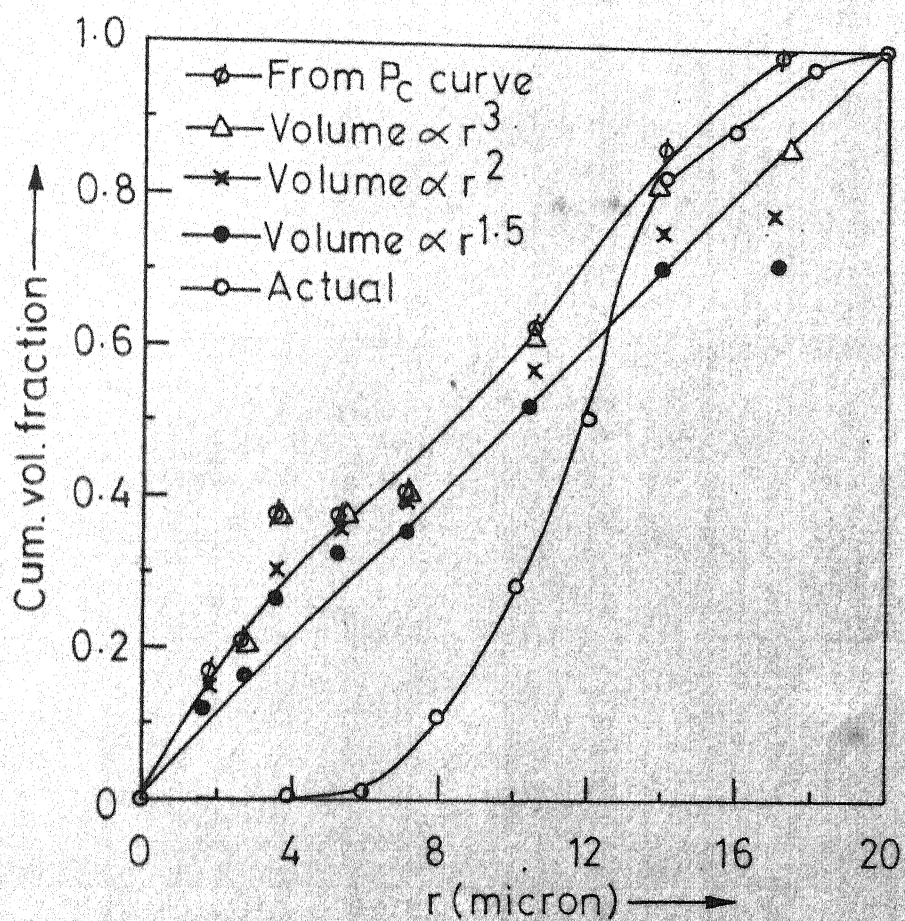


Fig.3f - Correction in volumetric distribution by Meyer's method. Network VI.



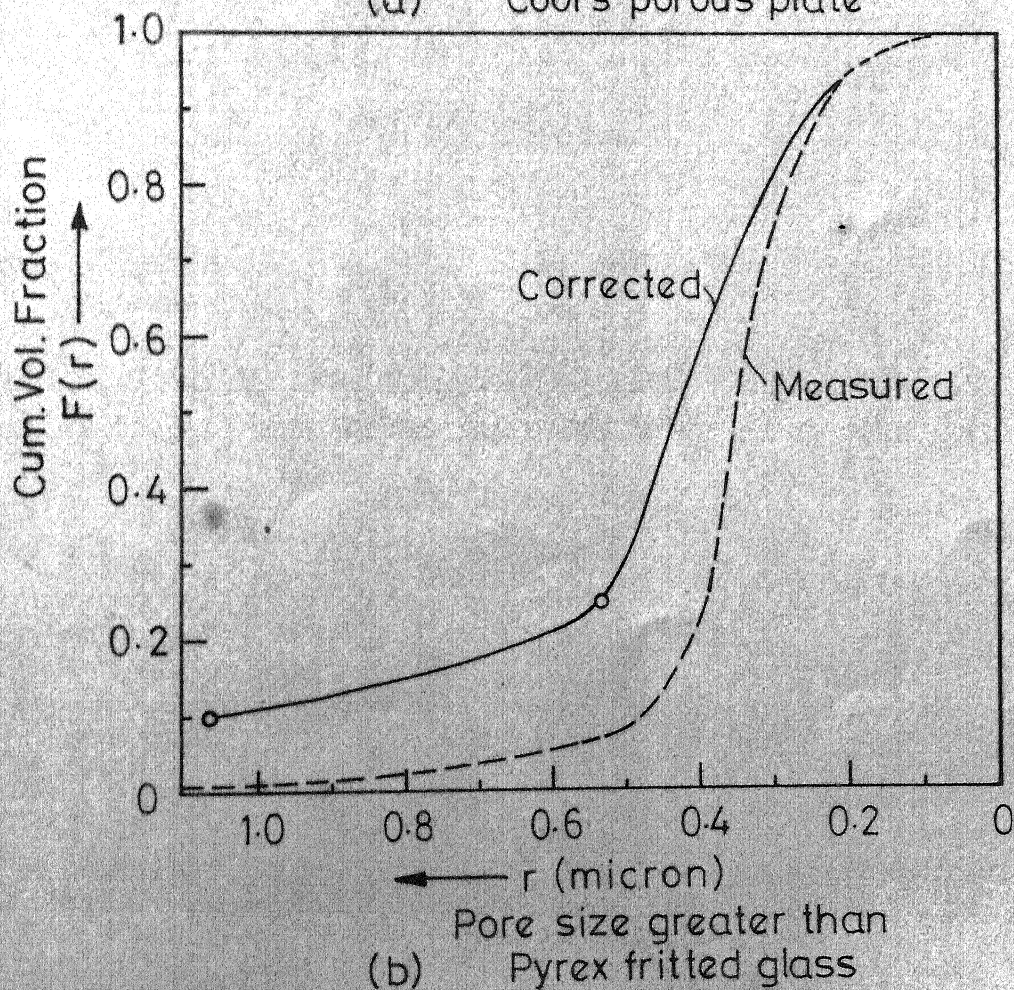
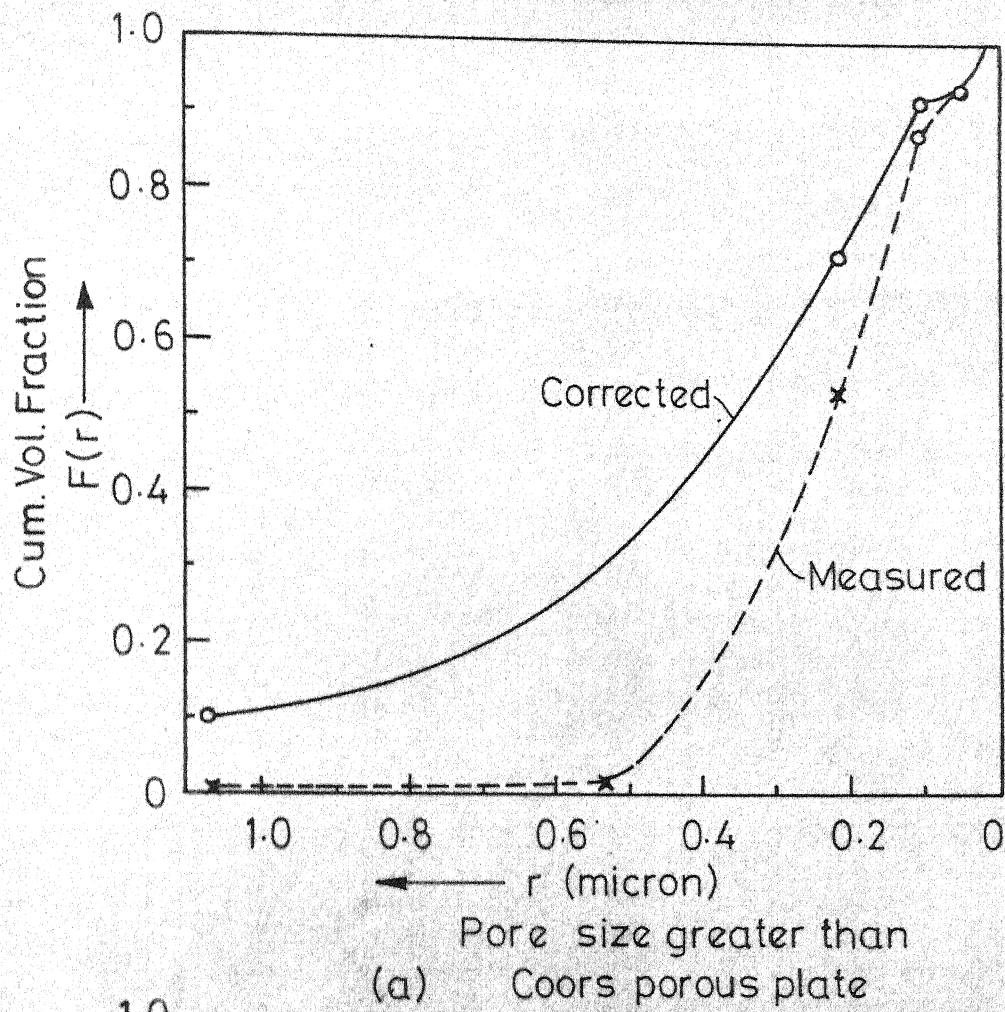


Fig. 4 -Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.

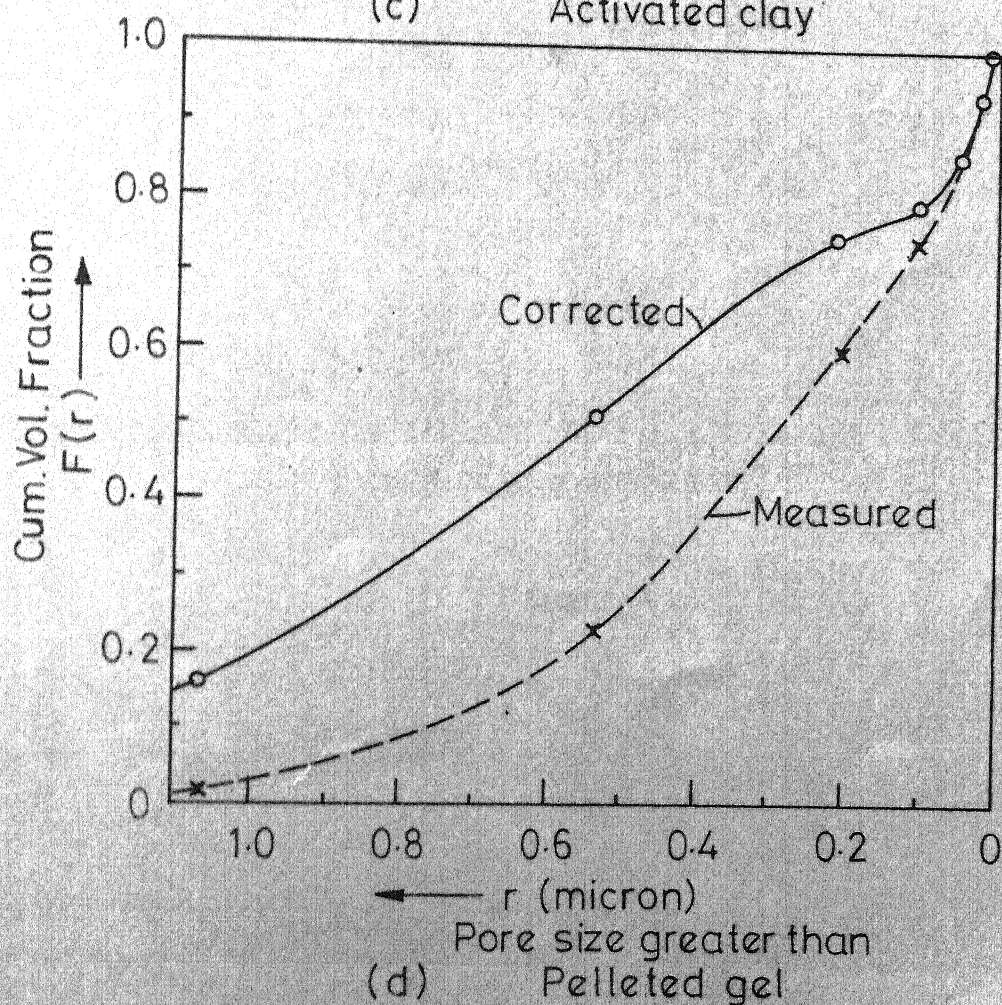
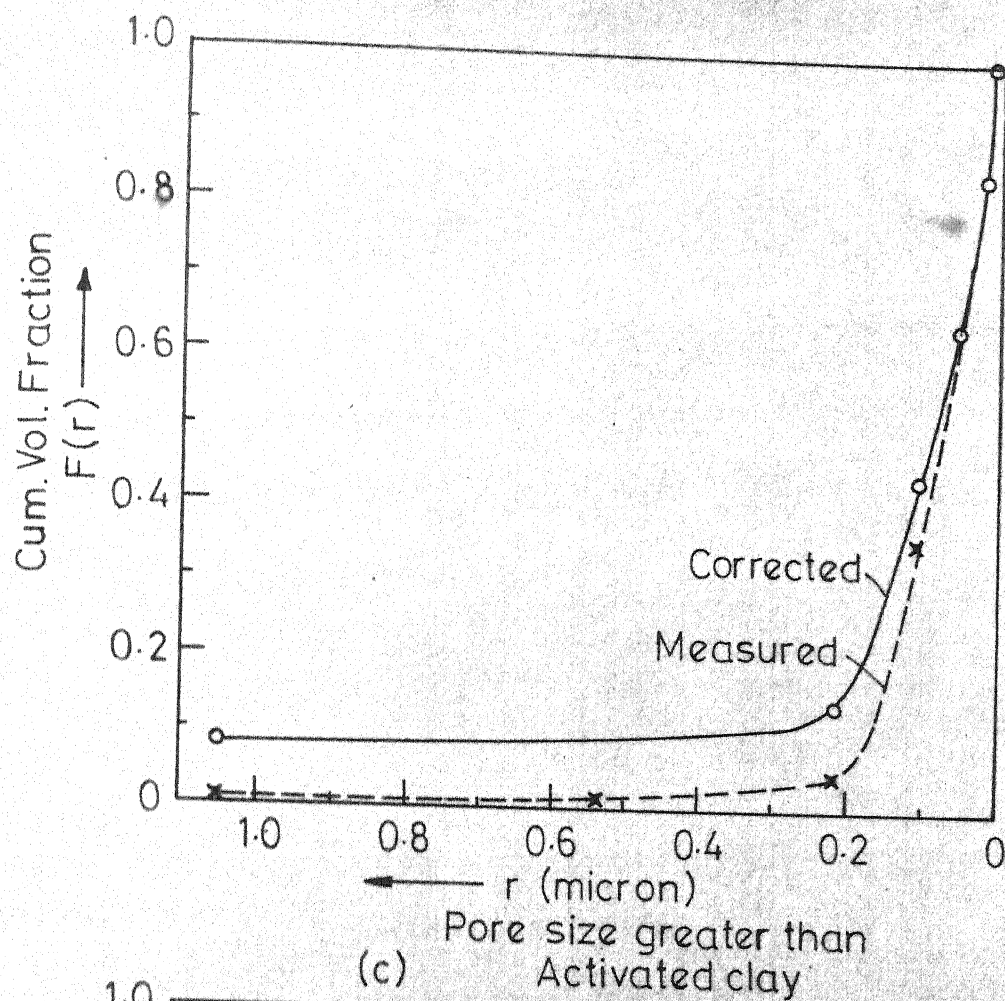


Fig. 4 - Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.



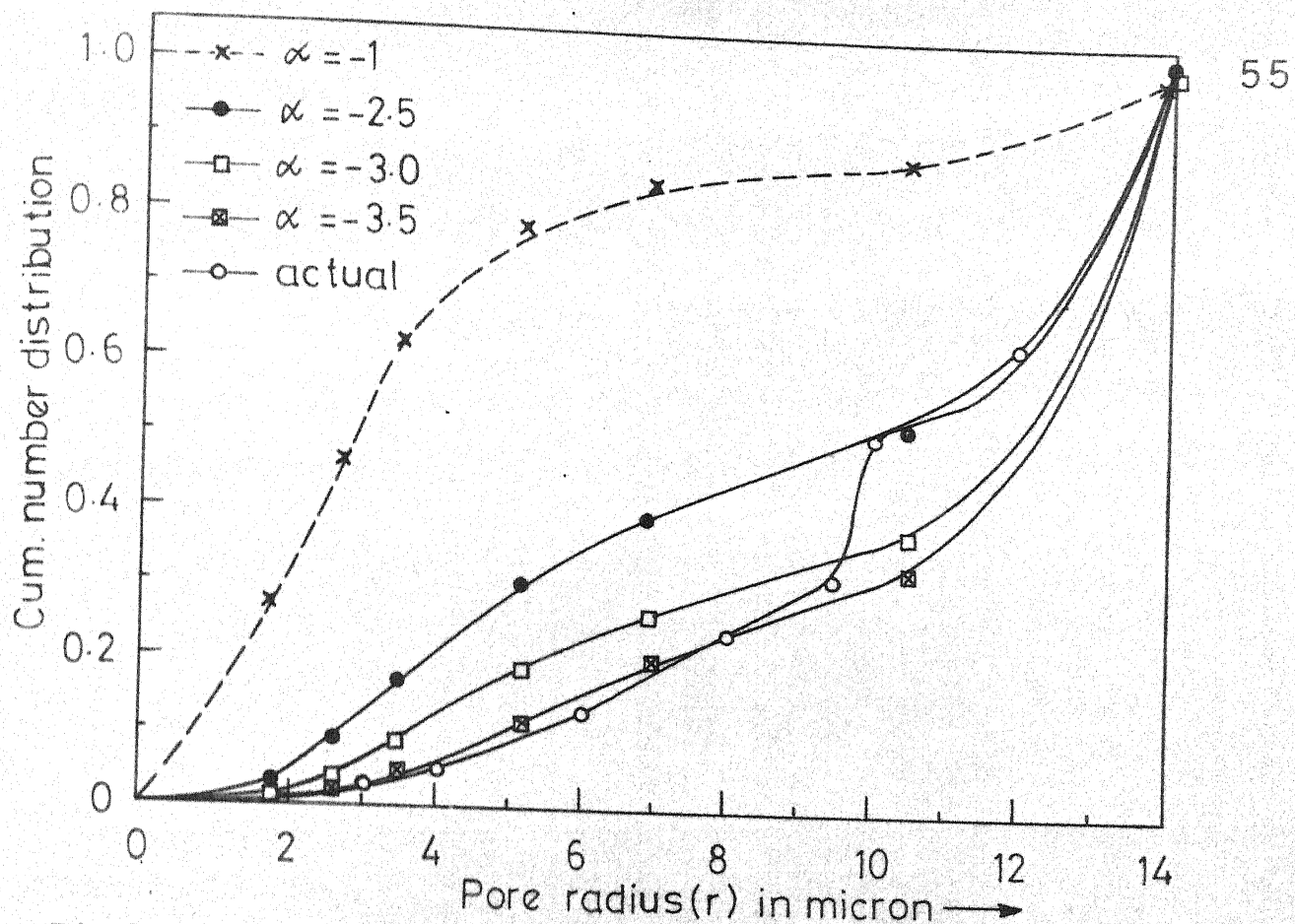


Fig. 5a - Comparison of calculated number distribution with actual network Fig. 1a.

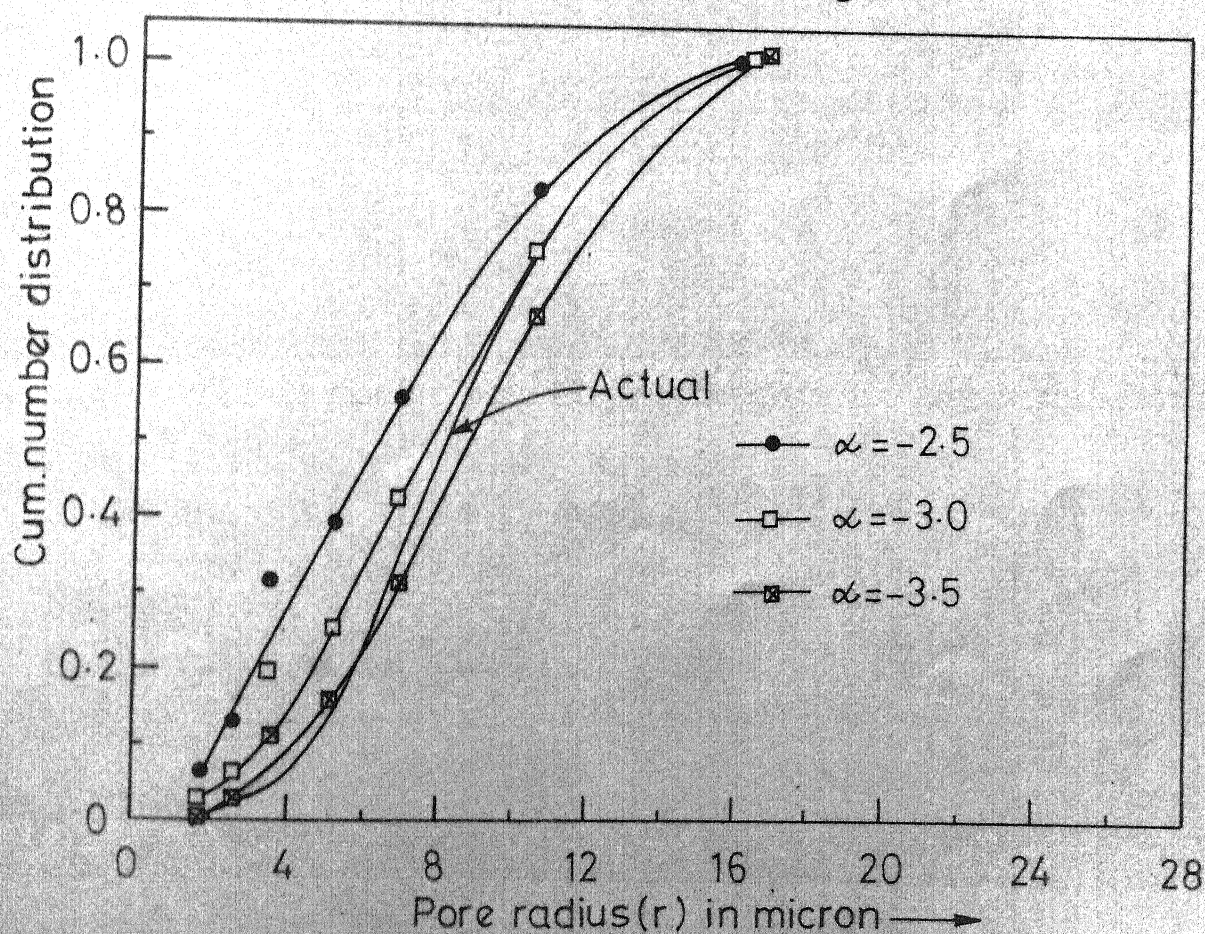


Fig. 5b- Comparison of calculated number distribution with actual Network Fig. 1b.

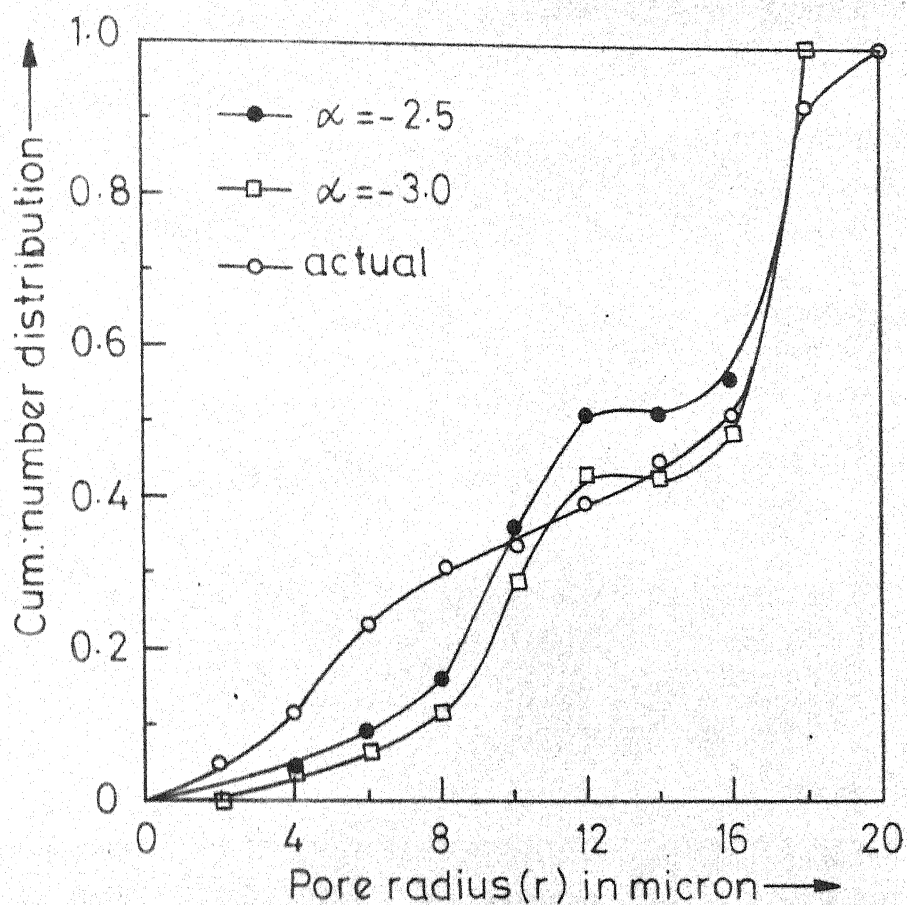


Fig.5c - Comparison of calculated number distribution with actual. Network Fig.1c.

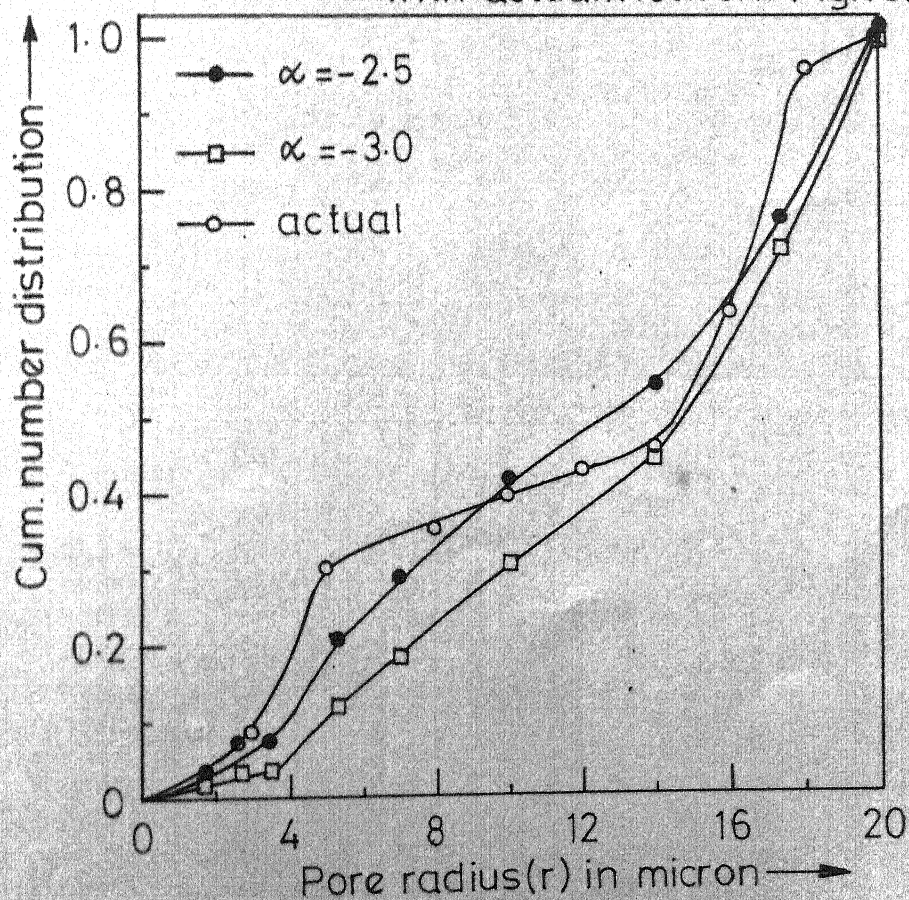


Fig.5 d - Comparison of calculated distribution with actual. Network Fig.1d.



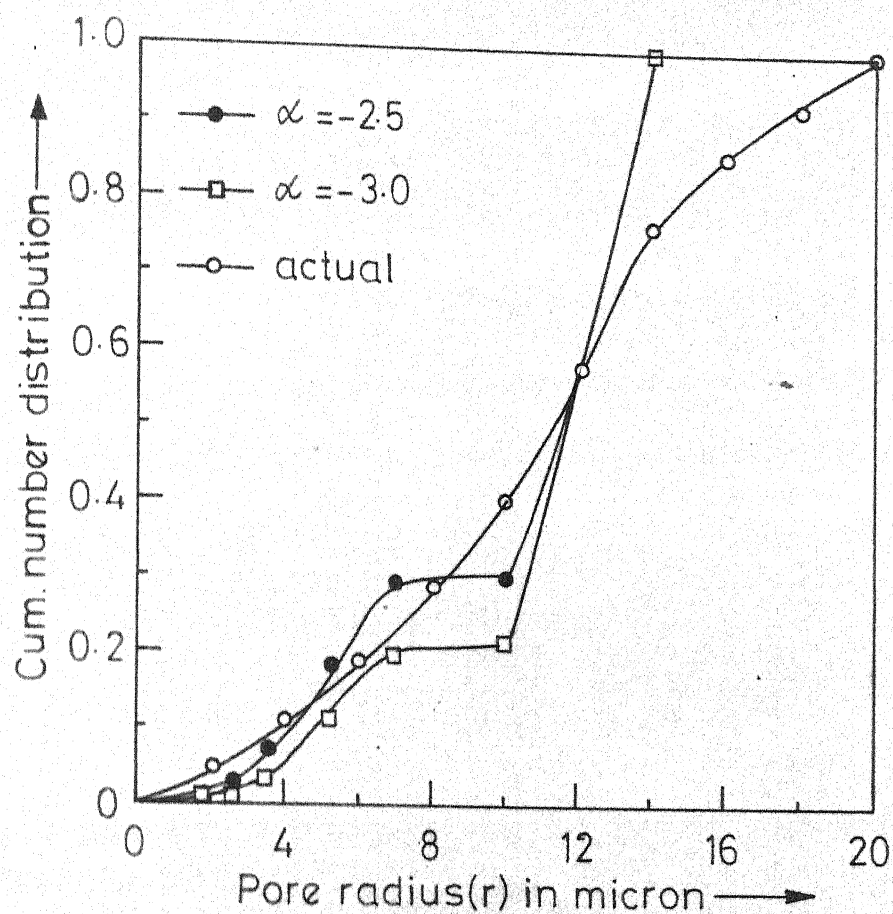


Fig. 5e-Comparison of calculated number distribution with actual. Network Fig. 1e.

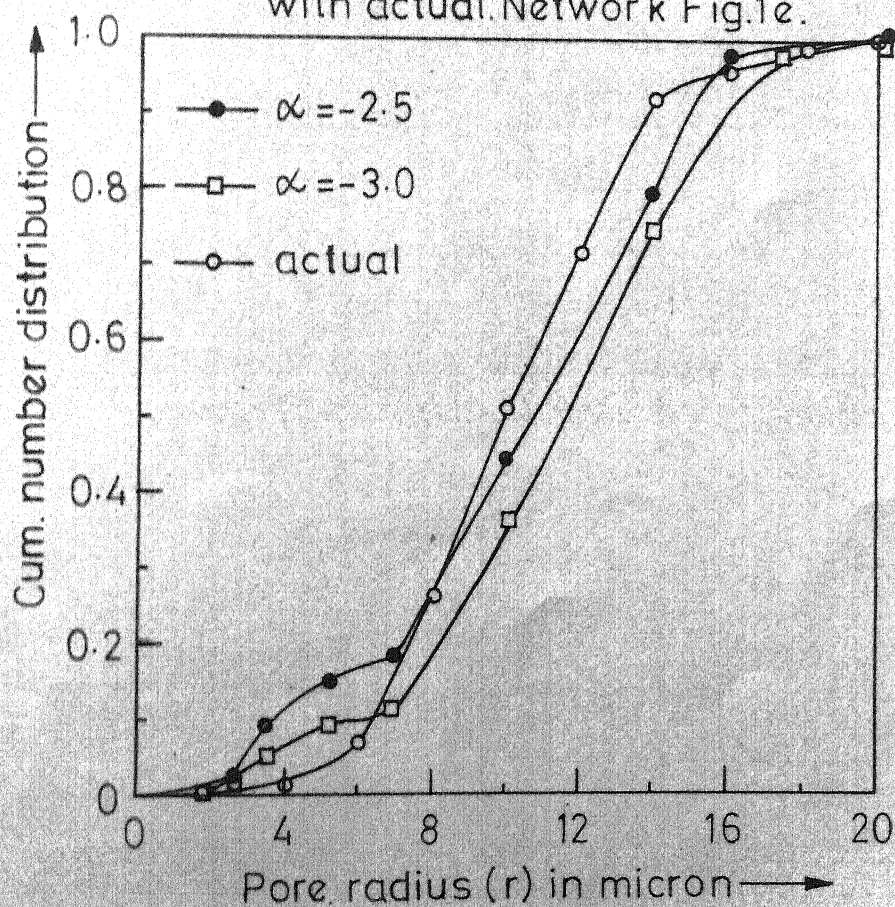


Fig. 5f-Comparison of calculated number distribution with actual. Network Fig. 1f.



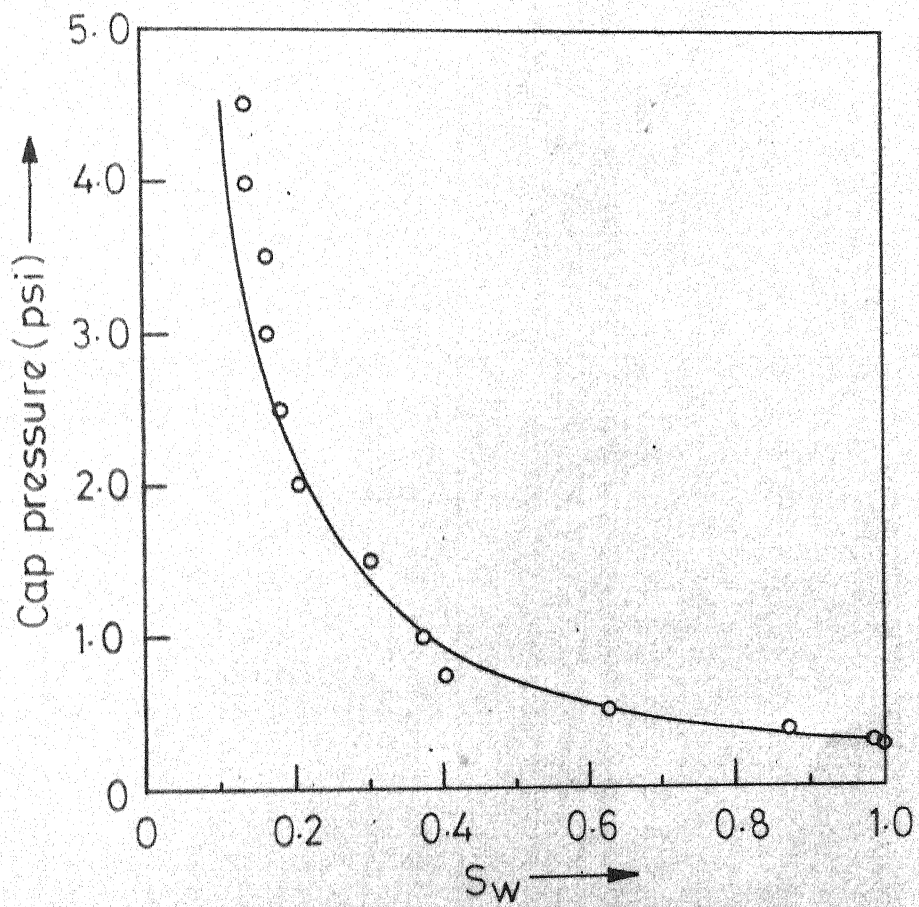


Fig. 6 -Least square fit of  $P_c$  data.  
Network VI.

TABLE 1INPUT DATA FOR NETWORK I

Network size	8 x 6 node points
Grid Spacing	112 $\mu$
Average opening at node points	25 $\mu$
Interfacial tension	20 dynes/cm
Contact angle (non wetting fluid)	180°
Viscosity(non wetting fluid)	0.8 C <sub>p</sub>
Viscosity (wetting fluid)	1.0 C <sub>p</sub>
Trapping factor	0.20
Time Step (initial)	200 $\mu$ sec.

Pore Size Distribution:

Radius ( $\mu$ )	Cum. Fraction (intended)	Cum. Fraction (adjusted)
0	0	0.25
3	0.0175	0.26328
4	0.047	0.28535
6	0.137	0.35234
8	0.27	0.45235
9.5	0.362	0.52189
10	0.576	0.68234
12	0.628	0.72150
14	1.0	1.0

\*\*\*

TABLE 2ARBITRARY DISTRIBUTION USED IN SIMULATION OF  
NETWORKS

Network III	Fore-Size ( $\mu$ )	Cum. Number Distribution
	0.0	0.0
	2.0	0.0434
	4.0	0.1304
	6.0	0.2608
	8.0	0.3478
	10.0	0.3912
	12.0	0.4346
	14.0	0.4780
	16.0	0.5650
	18.0	0.9130
	20.0	1.0
IV	0.0	0.0
	3.0	0.075
	5.0	0.325
	8.0	0.400
	10.0	0.450
	12.0	0.500
	14.0	0.550
	16.0	0.650
	18.0	0.950
	20.0	1.0

\*\*\*\*

TABLE 3

CAPILLARY PRESSURE DATA FOR SOME POROUS MATERIALS<sup>25</sup>

Materials	Volume of mercury(cc) injected per gm. of sample at pressure (psi)					
	100	200	500	1000	2000	5000
						10,000 (Macro pore vol.)
Coors Porous Flate	0.001	0.003	0.003	0.152	0.162	0.172
Tyrex Fritted Glass	0.001	0.012	0.159	0.168	0.169	0.169
Activated Clay	0.001	0.002	0.009	0.071	0.123	0.166
Pelleted Gel	0.003	0.040	0.108	0.133	0.152	0.168
						0.178

TABLE 4

COMPARISON OF EXPERIMENTAL PORE-SIZE DISTRIBUTION  
OBTAINED FROM MERCURY POROSIMETRY TO THAT CORRECTED  
BY MEYER'S METHOD

a) Coors Porous Plate

<u>Pore-Size (Micron)</u> <u>greater than equal</u> <u>to</u>	<u>Cum. Fractional</u> <u>Pore Volume</u> <u>Exptl.</u>	<u>Cum. Fractional</u> <u>Pore Volume</u> <u>Corrected</u>
1.066	0.00578	0.09797
0.533	0.01734	0.03578
0.213	0.53757	0.71379
0.1066	0.87861	0.92197
0.053	0.93642	0.93954
0.021	0.99422	0.99422
0.01060	1.00000	1.00000

b) Pyrex UF Fritted Glass

<u>Pore-Size (Micron)</u> <u>Greater than equal</u> <u>to</u>	<u>Cum. Fractional</u> <u>Pore Volume</u> <u>Exptl.</u>	<u>Cum. Fractional</u> <u>Pore Volume</u> <u>Corrected</u>
1.066	0.00592	0.10029
0.533	0.07101	0.24686
0.213	0.94083	0.94083
0.1066	0.99408	0.99408
0.05331	1.00000	1.00000
0.02132	1.00000	1.00000
0.01060	1.00000	1.00000

Table 4 (contd).

c) Activated Clay:

<u>Pore-Size (Micron) Greater than equal to</u>	<u>Cum. Fractional Pore Volume Exptl.</u>	<u>Cum. Fractional Pore Volume Corrected</u>
1.066	0.00513	0.08693
0.533	0.01026	0.01604
0.213	0.4615	0.14971
0.1066	0.36410	0.44945
0.05331	0.63077	0.63897
0.02132	0.85128	0.85128
0.01060	1.00000	1.00000

d) Pelleted Cell:

<u>Pore-Size (Micron) Greater than Equal to</u>	<u>Cum. Fractional Pore Volume Exptl.</u>	<u>Cum. Fractional Pore Volume Corrected</u>
1.066	0.1685	0.16701
0.533	0.22472	0.51417
0.2132	0.60674	0.75752
0.1066	0.74719	0.79563
0.05231	0.85393	0.85803
0.02132	0.94382	0.94382
0.01060	1.00000	1.00000

TABLE 5

CORRECTION FOR PORES OF LIMITED ACCESSIBILITY IN NETWORKS BY  
MEYER'S METHOD WITH DIFFERENT RELATION

BETWEEN  $l$  AND  $r$

Network	$P_c$ (psi)	$r$ (micron)	Cum. Vol. Frac. ( $S_w$ )	Cumulative Vol. Fraction Corrected by Meyer's Method		
				$l/r$	$l/r^0$	$l/r^{-0.5}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	0.37	14.0	1.0	1.0	1.0	1.0
	0.50	10.5	0.6920	0.476	0.557	0.473
	0.75	6.9	0.5948	0.565	0.549	0.503
	1.00	5.16	0.5155	0.500	0.479	0.443
	1.50	3.46	0.3685	0.361	0.354	0.309
	2.00	2.60	0.2603	0.261	0.253	0.196
	3.00	1.73	0.1747	0.176	0.170	0.119
	4.00	1.29	0.1523	0.152	-	-
	5.00	1.03	0.1378	0.138	-	-
II	0.259	20.0	1.0	1.0	1.0	1.0
	0.50	10.5	0.9096	0.879	0.8332	0.7963
	0.75	6.9	0.7287	0.722	0.663	0.622

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	1.0	5.16	0.5956	0.594	0.542	0.500
	1.5	3.46	0.5261	0.5261	0.500	0.420
	2.0	2.60	0.3181	0.3181	0.282	0.2003
	3.0	1.73	0.2354	0.2354	0.221	0.1373
	4.0	1.29	0.2226	0.2226	0.202	0.1273
III	0.259	20.00	1.0	1.0	1.0	
	0.287	18.00	1.0	1.0	1.0	
	0.323	16.00	0.7016	0.664	0.573	0.490
	0.370	14.00	0.6655	0.661	0.622	0.600
	0.430	12.00	0.6655	0.665	0.649	0.630
	0.516	10.00	0.5383	0.539	0.534	-
	0.646	8.00	0.3541	0.3541	0.354	0.347
	0.862	6.00	0.2829	0.2829	0.283	0.271
	1.290	4.00	0.2213	0.2213	0.221	0.220
	2.580	2.00	0.1015	0.1015	0.101	0.101
	2.58	2.00	0.1015			
	3.00	1.73	0.1015			



Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
IV	0.259	20.00	1.0	1.0	1.0	1.0
	0.300	17.4	0.8657	-	-	-
	0.370	14.00	0.7195	0.702	0.649	0.502
	0.50	10.5	0.6296	0.630	0.612	0.585
	0.75	6.9	0.5143	0.5143	0.512	0.495
	1.0	5.16	0.4307	0.4307	0.428	0.409
	1.5	3.46	0.2650	0.2650	0.2650	0.255
	2.0	2.6	0.2603	0.2603	0.260	0.242
	2.5	-	0.1936	0.1936	0.192	0.170
	3.0	1.73	0.1936	0.1936	0.191	0.166
	3.5	-	0.1831	0.1831	0.18	0.154
	4.0	1.29	0.1400	0.1400	1.33	0.110
V	0.30	17.4	1.0			
	0.37	14.0	1.0	1.0	1.0	1.0
	0.50	10.5	0.5186	0.505	0.421	0.331
	0.75	6.9	0.5081	0.5074	0.479	0.438
	1.0	5.16	0.4032	0.4032	0.380	0.343
	1.5	3.46	0.2763	0.2763	0.269	0.234

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2.0	2.6	0.2206	0.2206	0.210	0.171
	3.0	1.73	0.1900	0.1900	0.190	0.190
	4.0	1.29	0.1724	0.1724	0.172	0.172
VI	0.259	20.00	1.0	1.0	1.0	1.0
	0.30	17.4	0.9882	0.852	0.777	0.717
	0.37	14.0	0.8718	0.812	0.751	0.707
	0.50	10.5	0.6216	0.617	0.570	0.520
	0.75	6.9	0.4009	0.401	0.390	0.352
	1.0	5.16	0.3703	0.3703	0.358	0.322
	1.5	3.46	0.3702	0.3702	0.298	0.267
	2.5	2.6	0.2077	0.2077	0.202	0.163
	3.0	1.73	0.1653	0.1653	0.155	0.116
	4.0	1.29	0.1352	0.1352	0.122	0.089

TABLE 6

CALCULATION OF NUMBER CUM. DISTRIBUTION FROM  $P_c$  DATA  
OF NETWORKS BY FATT'S MODEL WITH MODIFIED EXPONENT

Network	$P_c$	r	$S_w$	Computed Number Distribution		
				$\alpha = -2.5$	$\alpha = -3.0$	$\alpha = -3.5$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	0.37	14.00	1.0	1.0	1.0	1.0
	0.50	10.5	0.6920	0.5247	0.3854	0.33
	0.75	6.9	0.5948	0.3962	0.26236	0.201
	1.00	5.16	0.5155	0.3086	0.1883	0.116
	1.50	3.46	0.3685	0.1716	0.0904	0.047
	2.0	2.60	0.2603	0.0310	0.011	0.0044
II	0.324	16.0	1.0	1.0	1.0	1.0
	0.5	10.5	0.91	0.831	0.752	0.667
	0.75	6.9	0.729	0.558	0.424	0.313
	1.0	5.16	0.596	0.390	0.258	0.161
	1.5	3.46	0.526	0.315	0.195	0.112
	2.0	2.6	0.318	0.130	0.064	0.029
	3.0	1.73	0.235	0.067	0.027	0.010
III	0.287	18.00	1.0		1.0	1.0
	0.323	16.00	0.70		0.485	0.560
	0.370	14.00	0.666		0.43	0.510
	0.430	12.00	0.666		0.43	0.510
	0.516	10.00	0.538		0.287	0.358

Table 6(contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	0.646	8.00	0.354		0.1184	0.16
	0.862	6.00	0.283		0.0678	0.090
	1.290	4.00	0.221		0.0365	0.042
	2.580	2.00	0.1015		0.0	0.0
IV	0.259	20.00	1.0	1.0	1.0	
	0.30	17.4	0.8657	0.76	0.72	
	0.37	14.0	0.7195	0.54	0.44	
	0.5	10.5	0.6296	0.418	0.305	
	0.75	6.9	0.5143	0.286	0.180	
	1.0	5.16	0.431	0.204	0.118	
	1.5	3.46	0.265	0.07	0.030	
	2.0	2.6	0.260	0.067	0.029	
	3.0	1.73	0.194	0.027	0.010	
V	0.37	14.0	1.0	1.0	1.0	
	0.50	10.5	0.5186	0.215	0.30	
	0.75	6.9	0.5081	0.202	0.29	
	1.00	5.16	0.4032	0.116	0.182	
	1.50	3.46	0.2763	0.035	0.07	
	2.0	2.6	0.2206	0.0128	0.03	
	3.0	1.73	0.190	0.0043	0.0115	

Table 6 (Contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
VI	0.259	20.0	1.0	1.0	1.0	
	0.30	16.0	0.988	0.98	0.977	
	0.37	14.0	0.8718	0.795	0.746	
	0.50	10.5	0.6216	0.4428	0.360	
	0.75	6.9	0.4009	0.1818	0.1144	
	1.00	5.16	0.3703	0.1514	0.091	
	1.50	3.46	0.3029	0.095	0.054	
	2.0	2.6	0.2077	0.0275	0.017	
	3.0	1.73	0.1653	0.002	0.0056	

# REFERENCES

1. Fatt, I, Network Model of Porous Media Parts I,II and III, Trans.AIME 207 p. 144 (1956).
2. Meyer, H.I., Pore Distribution in Porous Media, J. Appl. Phys., 24, p 510 (1953).
3. Dallavalle, J.M., Micromeritics, Pitman, N.Y. (1948).
4. Carman, P.C., The Flow of Gases in Porous Media, Butterworth Scientific Publications, London (1956).
5. Dullien, F.A.L. and Batra, V.K., ;Determination of the Structure of Porous Media, I&EC, 62 p. 25 (1970).
6. Gates, J.I. and Tempelaar Lietz, W.: Drill. and Prod. Practice, API, N.Y (1950).
7. Fatt, I. and Dykstra, H. : Trans.AIME 192 p 249 (1951).
8. Purcell, W.R., Trans.AIME, 186 p. 39 (1949).
9. Burdine, N.T., Gouray, L.S. and Reichertz, P.P.; Trans AIME 189 p. 195 (1950).
10. Gregg, S.J. and Sing, K.W. Adsorption, Surface Area and Porosity, p. 139, Academic Press (1967).
11. Kozeny, J: S.B.Akad.Wiss. Wien. Abt. IIa, 136 p.271(1927).
12. Carman, P.C. Trans. Inst. Chem. Eng. Lond. 15, p.150 (1937).
13. Haughey, D.P. and Beveridge, G.S.G.; Structural Properties of Packed Beds - A review. Can. J. Chem. Engg. 17, p.130 (1969).

14. Kruyer, S. ; Trans. Faraday Soc. 54 p. 1758 (1958).
15. Frevel, L.K. and Kressley, L.J.: Anal. Chem. 35 p.1492 (1963).
16. Meyer, R.P. and Stowe, R.A. : J. Colloid. Sci. 20, p. 893 (1965).
17. Meyer, R.P. and Stowe, R.A., J. Phys. Chem. 70, p.3867 (1966).
18. Melrose, J.C., Wettability as Related to Capillary Action in Porous Media, SPEJ 5(3) 1965.
19. Naar, J. and Wygal, R.J., Structure and Properties of Unconsolidated Aggregates. Can. J. Phys. 40<sup>2</sup> p.818 (1962).
20. Markin, V.S., Izv. Akad. Nauk. SSSR Ser. Khim. 11, p.1923 (1963).
21. Dodd, C.G. and Kiel, O.G.; J. Phys. Chem. 63 p. 1646 (1959).
22. Singhal, A.K., Partial Immobilization of Fluid Phases During Multiphase Flow Through Porous Media" Ph.D. Thesis, Univ. California (Berkeley) 1971.
23. Haring, R.E., and Greenkorn, R.A.: A Statistical Model of a Porous Medium with Non-uniform Pores", A.I.Ch.E.J. 16 (3) p.477 (1970).
24. Paytakes, Tien and Turian; A New Model for Granular Porous Media, Part I, A.I.Ch.E. J. p. 58, Jan. 1973.
25. Ritter, H.L. and Drake, L.C., Pore Size Distribution in Porous Material, Ind. Engg. Chem. 17 (analytical edition) p. 782 (1945).

26. Zwietering, P. The Structure and Properties of Porous Solids, p.287 Butterworth Publication (1958).
27. Dullien, F.A.L., Determination of Pore Accessibilities - an Approach, J.P.T. p. 14-15, Jan. 1969.
28. Leverett, M.C.; Capillary Behaviour in Porous Solids, Trans.AIME 142 p. 151 (1941).
29. Leverett, M.C., Lewis, W.B. and True, M.E., Dimensional Model Studies of Oil Field Behaviour, Trans.AIME 146, p.175 (1942).
30. Rose, W. and Bruce, W.A.; Evaluation of Capillary Character in Petroleum Reservoir Rock, Trans.AIME 186, p. 127 (1949).
31. Fatt, I., In Discussion of Paper, 'Evaluation of Monte-Carlo Methods in Studying Fluid-Fluid Displacement and Wettability in Porous Rocks' by C.G. Dodd and O.G. Kiel (Ref. 21).
32. Wienbrandt, R.M. and Fatt, I.: A Scanning Electron Microscope Study of the Pore Structure of Sandstones, JPT, p.543 May 1969.

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## APPENDIX A

### NETWORK MODEL: FLOW COMPUTATION

#### Pressure Computation:

Assuming that flow in the pore channels of a porous system is essentially viscous in nature ( $Re < 75$ ), Poiseuille's law of viscous flow could be applied for flow computation in each tube of the network. For single phase flow in a cylindrical tube of length  $l_i$  and radius  $r_i$ , the expression for flow rate,  $q_i$  is given as:

$$q_i = \frac{\pi r_i^4}{8\mu} \frac{\Delta P}{l_i} \quad (A.1)$$

or

$$q_i = K_i \Delta P_i$$

where  $\Delta P_i$  is the pressure differential causing flow in the  $i$ th tube. For multiphase flow  $K_i$  and  $\Delta P_i$  may be modified depending upon the relative proportion of the different fluids present and the nature of the flow regime respectively. Knowing total fluid conductivity,  $K_i$ , of each tube and maintaining total volumetric balance a Kirchoff type equation can be written for each node point of the network:

$$\sum_{\substack{s=1,8 \\ k=i-1, i+1 \\ l=j-1, j+1 \\ (i,j) \neq (k,l)}} K_s [(P_{i,j} - P_{k,l}) + P_c] = 0 \quad (A.2)$$

Knowing the values of  $K_s$ ,  $P_c$  and the pressure at the boundaries, the set of simultaneous algebraic equations can be solved by Gauss-elimination technique.

#### Capillary Pressure:

Capillary pressure,  $P_c$ , is applicable only to those pores which undergo displacement flow. For single phase, slug or annular flow regimes, capillary pressure is essentially zero. In this computation  $P_c$  is taken as equal to the pressure required to squeeze an fluid/fluid interface from a mode point opening (radius  $r_{no}$ ) to a tube of radius  $r_i$  ( $r_{no} > r_i$ ). For a tube of triangular cross-section

$$P_c = 1.78 \gamma \cos \theta \left( \frac{1}{r_{no}} - \frac{1}{r_i} \right) \quad (A.3)$$

where  $\gamma$  = interfacial tension and  $\theta$  is the contact angle which in our case is the receding contact angle.

#### Flow Behaviour in a Single Tube:

##### i) Single Phase Flow:

The total volumetric flow rate through a tube of triangular (equilateral) cross section, with the radius of the inscribed circle,  $r$ , viscosity of the fluid  $\mu$ , and pressure gradient  $\Delta P / \Delta l$ , is

$$q = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu} \frac{\Delta P}{\Delta l} \quad (A.4)$$

##### ii) Annular Flow:

We used modified Yuster relationship as suggested

by Singhal<sup>22</sup> for flow computation.

$$q_w = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_w} \frac{\Delta P}{\Delta l} S_w^2 \quad (A.5)$$

$$q_n = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_n} \frac{\Delta P}{\Delta l} \left[ (2S_n \frac{\mu_n}{\mu_w} + S_n^2 (1 - 2 \frac{\mu_n}{\mu_w})) \right] \quad (A.6)$$

where S denotes saturation and subscripts w and n denote wetting and non-wetting phase respectively.

(iii) Slug Flow:

Total flow rate is given by

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n + 6a\mu_w)} \frac{\Delta P}{\Delta l} \quad (A.7)$$

where a is the side of the triangular cross section.

(iv) Displacement Flow:

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n)} [\Delta P \pm P_c] \quad (A.8)$$

#### Selection of Tube for Flow Change:

Depending on the availability of fluids at a node point, transition between flow regimes will occur. In many instances, channels leaving a node point may be capable of carrying more of a particular phase (fluid) than is available at that time. In such cases, saturation and flow regime changes in the tubes will have to occur to unload all available fluids. A table of possible transition between flow regimes is given in Table A-1. Some times there may exist more than one pore which might be undergoing flow in the regime to be altered. Selection of tubes

for flow changes in such cases is done by Monte-Carlo method with a bias for flow capacities of the competing tubes.

#### General Scheme for Flow Computation:

Words in block capital letters are subroutine name referred to in the program listing.

The network is generated in the program by SIMU with specified pore-size distribution and grid size. This subroutine also computes the volume of the pores connected to each node point and flow conductivities to the two fluids. Other data; fluid viscosities, interfacial tension, pressure differential across the model and contact angle, are read in the main program CALC. The radius of the opening at the node points,  $r_n$ , is chosen to be slightly larger than the largest tube radius of the network.

The next step is to determine the pressure distribution in the model. Pressure at each node point is computed by solving the system of equation A-2 by PRSOL through SOLVE. Apart from updating the conductivities of each tube after every time step, SOLVE also immobilizes those tubes which may cause outflow from the first row and inflow from the last row. Also, those tubes, whose capillary pressure is greater than the pressure differential available and are oppositely directed, are blocked by the action of trapping factor. When a tube is blocked its conductivity is set equal to zero and the system of equations A-2 is solved. This is repeated till no more

tubes are blocked. While calculating  $P_c$  for tubes in the first row, the node point opening is assumed to be infinite. For other rows the specified value of  $r_n$  is used for the calculation.

The total outflow of each phase (fluid) from each node point is calculated under the existing pressure distribution by FLOW. Outflow from a tube is entered as inflow to the connected node point by COND(1). The imbalance between inflow and outflow of a particular phase at a node point is corrected by CHANGE which also effects the flow changes necessary for this correction. The capillary pressure and flow conductivities for the corrected flow distribution is computed by COND(2) and stored. Outflow from the model is obtained by adding together the inflow to the last row of node points. The volume of the fluid left in the model is computed to evaluate the saturation. This process is repeated till the equilibrium wetting phase saturation in model is obtained for that pressure drop.

#### Steps of Computation:

(i) Call SIMU to simulate the network model. Assign tube sizes, locations etc. Calculate the volume of each tube, its conductivity to displacing and displaced fluids.

(ii) Call SOLVE to update the conductivities through COND(2) and solve the system of equations A.2 by PRSOL to evaluate the absolute pressure at each node point. In case some of the tubes are blocked, call COND(1) to zero the

conductivity of those tubes and again call PRSOL to solve the system of equation A-2. Repeat till no more tubes are blocked.

(iii) Choose node points in descending order of absolute pressure and call FLOW to calculate outflow of each fluid from each tube and node point.

(iv) Calculate imbalance at each node point to test whether overall material balance of incoming and outgoing fluids is satisfied.

(v) Imbalance in the material balance of each phase is removed by assigning the excess incoming phase to various tubes by Monte Carlo method through CHANGE without forcing flow change in the tubes.

(vi) Assign outflow from each tube as the inflow to the connected down-stream node points.

(vii) In case of back flow, calculate inflow to those tubes and node points in FLOW. If there is any imbalance either in total fluid at the connected node points or imbalance in any phase in any tube, call CHANGE to assign the differential volume to various tubes.

(viii) Calculate outflow from the model by adding the inflow to each node points in the last row of the network.

(ix) Calculate total fluid volume left in the model by adding the volume of the fluid in each tube at the end of the time interval.

(x) Calculate the saturation for each phase.

(xi) Repeat steps (i) to (x) till there is practically no change in the total outflow from the model in the successive time steps (less than 1% of the outflow in the first time step) for the same  $\Delta P$ .

(xii) Test whether the sum of the cumulative outflow and the volume of fluid remaining in the network for each fluid at the end of every time step is constant.

(xiii) Repeat the sequence of operations with higher  $\Delta P$ , to get the value of equilibrium  $S_w$  (wetting phase saturation) for different  $P_c$ . Thus  $P_c$  curve is generated.



TABLE A-1TRANSITION BETWEEN FLOW REGIMES

Flow Regimes To / From	Single Phase	Displacement	Slug	Annular
Single Phase	x	1*	1*	1
Displacement	2	x	-	-
Slug	-	-	x	1
Annular	-	1**	1	1

x No change in flow regimes.

1 Easy transition.

2 Transition influenced by capillary forces.

- Transition not possible without going through other flow regimes.

\* Modified single phase flow for non-wetting flow because of a film of wetting fluid at the pore walls.

\*\* Possible only for non-wetting phase displacing the wetting phase.

\*\*\*

## APPENDIX B

### MEYER'S METHOD

The radius  $r$  of a pore is defined to be equal to the radius of a capillary tube which will just allow mercury to enter it against capillary force at the same pressure as that at which the pore will fill, if connected to a mercury source.

Let  $\lambda(r)$  be the fraction (volumetric) of the total void space occupied by  $r$ -pores i.e. pores whose radii lie in the range  $r$  to  $r+dr$ . The number of such  $r$  pores in a unit volume will be given by

$$a(r) dr = \frac{f \lambda(r)}{Kr^3} \quad (B.1)$$

where  $f$  = fractional porosity

$Kr^3$  = vol. of a single pore of radius  $r$

It is necessary to designate one representative point in the interior of each pore which we shall term "centre of the pore". For our purpose, any point will do so long as it is not too close to the wall of the pore and is consistently chosen, e.g. cg. of the void space will serve. Also, we define a volume  $dv$  so small that the probability of the centres of two or more  $r$ -pores being located in this volume may be neglected.

Let the probability of  $m$   $r$ -pores being located in any volume  $v$  be  $\psi_m(v, r)dr$ . Then for randomly distributed pores

$$\begin{aligned} \psi_m(v+dv, r) dr &= \psi_m(v, r) dr [1 - (a dr) dv] + \\ &\quad \psi_{m-1}(v, r) dr (a dr) dv \end{aligned} \quad (B.2)$$

which on re-arranging gives

$$\frac{d(\psi_m dr)}{dv} = \frac{[(a dr)v]^m}{m!} \exp[-(a dr) v] \quad (B.3)$$

Now we define a volume  $v(r_0, r)$  such that, if an  $r$ -pore is located in  $v(r_0, r)$ , it may be expected to be connected to an  $r_0$ -pore. This can be done if we assume that two pores are connected if the centre of the smaller lies in a volume adjacent to the larger pore, which is the difference between the volume of a pore whose radius equals the sum of the radii of the two pores minus the volume of the larger pore i.e. for  $r_0 > r$

$$v(r_0, r) = K(r_0 + r)^3 - Kr_0^3 = K(3r^2 r_0 + 3r r_0^2 + r^3) \quad (B.4)$$

Now if in Eq.(B-3)  $v$  is replaced by  $v(r_0, r)$ , we get the probability of  $m$   $r$ -pores all being joined to the same  $r_0$ -pore. The probable number of such groups of pores which would exist in a unit volume would be given by the product of this probability times the number of  $v(r_0, r)$  volumes in a unit cube (which is equal to the number of  $r_0$  pores in a unit cube). This number is equal to

$$\begin{aligned} &a(r_0) dr \psi_m(v(r_0, r), r) dr \\ \text{or} \quad &a(r_0) dr \psi_m(r_0, r) dr \end{aligned}$$

We are here interested in  $\Psi_0(r_0, r)dr$  which is the probability of an  $r_0$  pore not being connected to an  $r$ -pore.

Let a porous rock be subjected to mercury pressure such that all pores of radius  $\geq r$  would fill if they had access to mercury, and let  $f(r)$  be the measured fraction of the pore volume that is filled up with injected mercury at that pressure. Let  $\theta(r)$  be the actual fraction of the pore-volume devoted to pores of radius  $\geq r$ .

If the simplifying assumption is made that only pores of radius  $\geq r$  which will fail to fill are those that are not connected to any other pores of equal or larger radius. That is the probability of an  $r_0$  pore failing to fill is given by the multiplicative law of probability  $\int_{r_0}^{\infty} \Psi_0(r_0, r)dr$ .

The total number of pores of radius  $\geq r_0$  which will fail to fill is given by the expression

$$\Psi(r_0, r) = \int_{r_0}^{\infty} a(r)dr \left\{ \int_r^{\infty} \pi \Psi_0(r_0, r) dr \right\} \quad (B.5)$$

$$\text{Hence } f(r) = \theta(r) \left[ 1 - \frac{\Psi(r_0, r)}{\int_{r_0}^{\infty} a(r)dr} \right] \quad (B.6)$$

This is the expression from which we shall obtain true pore-size distribution  $\theta(r)$  from the actual distribution  $f(r)$ .

#### Numerical Approximation:

Since the above expression is not convenient for numerical calculation the following approximation are used. The radius  $r$

is discretized so that it takes only a finite number of values  $r_n < r_{n-1} < \dots < r_1$  and

$$\Delta r_i = r_{i-1} - r_i \quad i = 1, 2, \dots$$

$$a_i = \int_{r_i}^{r_{i-1}} a(r) dr$$

$$Y_i = \Gamma(r_i) - \Gamma(r_{i-1})$$

$$\nu_i = \Theta(r_i) - \Theta(r_{i-1})$$

$$\psi_{ij} = \exp[-a_i v(r_i, r_j)]$$

$$\Gamma(r_i, r_j) = \sum_{k=1}^i a_k \prod_{l=1}^j \psi_{kl}$$

Substituting these expressions in Eq. (B.6) gives the approximate equation

$$\Gamma(r_i) = \sum_{k=1}^i Y_k = \sum_{k=1}^i \nu_k \times \left[ 1 - \frac{\sum_{k=1}^i a_k \prod_{l=1}^j \psi_{kl}}{\sum_{k=1}^i a_k} \right] \quad (B.6a)$$

Algorithm:

- (1) Assume a value of  $\nu_i$  and calculate  $a_i$  and  $\psi_{ij}$ .
- (2) Using these values solve Eq. (B.6a) for  $\nu_i$ .
- (3) If computed  $\nu_i$  value is not close enough to the assumed value, make another assumption and repeat this process.

\*\*\*

APIENDIX CGLOSSARY OF TERMS USED

Porosity (f) is the ratio between the void space and bulk volume in a porous medium.

Capillary Pressure ( $P_c$ ) is the difference in pressures across a fluid/fluid interface. Capillary pressure curve describes the changes in capillary (threshold) pressure of a porous as a function of its fluid saturation.

Threshold Pressure ( $P_T$ ) is the minimum excess pressure must be maintained in the non-wetting phase to enable it enter a given porous medium.

Saturation(S) of any fluid in a porous medium is the ratio between the volume of the fluid in the medium to its pore volume.

Contact Angle ( $\theta$ ) is the angle (through the displacing phase) that the fluid/fluid interface makes with the surface of the porous medium.

Wetting Phase is the fluid in a porous medium whose contact angle with the solid surface is less than  $90^\circ$ . If the contact angle is more than  $90^\circ$  it is called non-wetting phase.

\*\*\*\*

APPENDIX DPROGRAM LISTING OF MEYER'S METHOD

N	Number of data in the set
SIGMA	Interfacial tension
THETA	Contact angle of non-wetting phase
POR	Porosity
R(I)	Pore-size corresponding to P(I)
PC	Capillary pressure
SGAMA	Cumulative Volume of Mercury Injected.
ESTNU	Assumed value of nu
NU	Computed nu
DIFNU	Difference between estimated and computed nu
SV(I,J)	$v(r_i, r_j)$ ; characteristic volume
PSI(I,J)	$\psi_{ij}$
PSIR(I,J)	$\psi_i$



## FORTRAN SOURCE LIST

ISN SOURCE STATEMENT

```

0 $IBFTC MAIN
C MEYERS METHOD
C PC IN PSI
C CAT=1.0 MEANS THE USUAL VALUES OF CHANGE ARE NOT TO BE USED
1 COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
2 COMMON/A2/RS(20),RC(20),SIGMA
3 COMMON/A3/NU(500),POR
4 DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500),ESTNU(500)
5 REAL NU
6 READ 60,N
10 60 FORMAT(I4)
11 PRINT120
12 120 FORMAT(1H1 )
13 READ62,SIGMA,THETA
14 62 FORMAT(5F10.3)
15 65 FORMAT(5F10.5)
16 THETA= THETA*3.1416/180.
17 READ62,POR
20 PRINT50,THETA
21 50 FORMAT(5X,*THETA=*,F10.5)
22 N=N+1
23 DO12 I=2,N
24 R(I)=0.0
25 RS(I)=0.0
26 RC(I)=0.0
27 A(I)=0.0
30 SUMA(I)=0.0
31 DO 12 J=1,N
32 SV(I,J)=0.0
33 PSI(I,J)=0.0
34 PSIR=0.0
35 12 CONTINUE
40 DO 101 IK=2,N
41 101 READ65,P(IK),SGAMA(IK)
43 PRINT20,(P(IK),IK=2,N),(SGAMA(IK),IK=2,N)
54 DO 40 IM=2,N
55 40 SGAMA(IM)=SGAMA(IM)/POR
57 PRINT5
60 5 FORMAT(5X,12HACTUAL VALUE ,10X,2HIK ,5X,10HTRUE VALUE /)
61 DO10 J=2,N
62 CAT=0.0
63 DIFNU(1)=0.0
64 IK=2
65 ESTNU(IK)=SGAMA(J)
66 2 CALL SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,J,J)
67 IF(IK.EQ.2.AND.J.EQ.2)PRINT20,(R(I),I=1,N)
76 IF(IK.EQ.2.AND.J.EQ.2)PRINT20,((SV(I,IJ),IJ=2,N),I=2,N)
111 20 FORMAT(5X,8E15.8)
112 NU(IK)=SGAMA(J)/(1.-PSIR/SUMA(J))
113 DIFNU(IK)=NU(IK)-ESTNU(IK)
114 IF(DIFNU(IK).GT.0.0.AND.DIFNU(IK-1).LT.0.0)GO TO 25
117 IF(DIFNU(IK).LT.0.0.AND.DIFNU(IK-1).GT.0.0) GO TO 25
122 IF(ABS(DIFNU(IK)).LE.0.0002) GO TO 7
125 IF(CAT.EQ.1.0)GO TO 25
130 IF(ESTNU(IK).GT.0.0001)CHANGE=0.0001

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CGG145	ISN	SOURCE STATEMENT	FORTTRAN SOURCE LIST MAIN
133		IF(ESTNU(IK).GT.0.001)CHANGE=0.001	
136		IF(ESTNU(IK).GT.0.01)CHANGE=0.01	
141		IF(ESTNU(IK).GT.0.1)CHANGE=0.1	
144		IF(ESTNU(IK).GT.0.9)CHANGE=0.005	
147		IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE	
152		IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE	
155		IK=IK+1	
156		IF(IK.GE.500) GO TO 7	
161		GO TO 2	
162	25	CHANGE=CHANGE/2.	
163		IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE	
166		IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE	
171		IK=IK+1	
172		CAT=1.0	
173		GO TO 2	
174	7	PRINT 6,SGAMA(J),IK,ESTNU(IK)	
175	6	FORMAT(5X,F10.5,10X, 15,5X,F10.5)	
176	10	CONTINUE	
200		PRINT8,(A(J),SUMA(J),J=2,N)	
205	8	FORMAT(10X,E15.7,10X,E15.7)	
206	22	STOP	
207		END	

IBMAP ASSEMBLY MAIN

NO MESSAGES FOR ABOVE ASSEMBLY

CGG145  
ISN

## SOURCE STATEMENT

## FORTRAN SOURCE LIST

```

0 $IBFTC SUB1
1 SUBROUTINE VOL(P,R,THETA,IK,N,SV,M,IM)
2 COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
3 COMMON/A2/RS(20),RC(20),SIGMA
4 COMMON/A3/NU(500),FOR
5 DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500)
6 FACTOR=1./68947.3*1C.**4
7 DO 1 I=2,N
10 R(I)=FACTOR*2.*SIGMA*COS(THETA)/P(I)
11 R(I)=ABS(R(I))
12 RS(I)=R(I)**2
13 1 RC(I)=R(I)**3
15 R(1)=20.0
16 RS(1)=R(1)**2
17 N1=N+1
20 DO 6 I=2,N
21 DO 6 J=2,N
22 IF(R(J).GT.R(I))GO TO 7
25 5 SV(I,J)=2.*R(I)*R(J)+RS(J)
26 GO TO 6
27 7 SV(I,J)=2.*R(I)*R(J)+RS(I)
30 6 CONTINUE
33 DO10 I=2,N
34 DO10 J=2,N
35 10 SV(I,J)=ABS(SV(I,J))
40 RETLRN
41 END

```

CGG145

IBMAP ASSEMBLY SUB1

NO MESSAGES FOR ABOVE ASSEMBLY

CGG145 ISN SOURCE STATEMENT FORTRAN SOURCE LIST

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0 $IBFTC SUEZ
1 SUBROUTINE SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,IL,JK)
2 COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
3 COMMON/A2/RS(20),RC(20),SIGMA
4 COMMON/A3/NU(500),FCR
5 DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500),ESTNU(500)
6 REAL NU
7 CALL FLUN(99999)
10 N1=N
11 NU(IK)=ESTNU(IK)
12 SUMA(1)=0.0
13 IF(JK.EQ.2)CALLVOL(P,R,THETA,IK,N,SV,M,IM)
16 I=IL
17 A(I)=NU(IK)*(1./R(I)-1./R(I-1))*POR
20 DO 12 J=2,N1
21 B=-A(I)*SV(I,J)
22 IF(B.GE.88.0) GO TO 1
25 IF(B.LE.(-88.0)) GO TO 2
30 PSI(I,J)=EXP(B)
31 GO TO 12
32 1 CONTINUE
33 3 PSI(I,J)=1.0E30
34 GO TO 12
35 2 CONTINUE
36 4 PSI(I,J)=0.0
37 12 CONTINUE
41 J=JK
42 DO 8 K=2,IL
43 TEMP(I,J)=0.
44 PROD=1.
45 DO 10 L=2,JK
46 DELTA=R(L-1)-R(L)
47 PROD=PROD*PSI(K,L)
50 IF(PROD.LE.0.1E-37) PROD=0.0
53 10 CONTINUE
55 8 TEMP(I,J)=TEMP(I,J)+A(K)*PROD
57 PSIR=TEMP(I,J)
60 9 CONTINUE
61 SUMA(I)=SUMA(I-1)+A(I)
62 5 FORMAT(5X,8E15.7)
63 RETURN
64 END

```

CGG145

IBMAP ASSEMBLY SUB2

NO MESSAGES FOR ABOVE ASSEMBLY

CGG145

IBLDR -- JOB 000000

\*\*\* OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT 16 HRS. 21 MTS.

APPENDIX EPROGRAM LISTING NETWORK MODEL

The first subscript in each variable in the program refers to the node point.

X(1) to X(8)	The radii of the 8 tubes
X(9) to X(16)	Length of the tubes
X(17) to X(24)	Fluid content and flow regimes in the tubes
1.0	wetting (one phase flow)
2.0	non-wetting (one phase flow)
3.0	Displacement (non-wetting close to the node point)
3.5	Displacement (wetting closer to the node point)
4.1	Annular flow (displaced phase wetting)
4.2	Annular flow (displacing phase wetting)
4.5	Slug flow
X(25) to X(32)	Flow or no flow situation
1.0	Flow occurring
2.0	Flow blocked
1.5	Flow provisionally blocked
2.5	Flow permanently blocked
X(33) to X(40)	Flow conductivities of the tubes to displaced fluid
X(41) to X(48)	Flow conductivities of the tubes to displacing fluid
X(49) to X(56)	Volume of the tubes
X(57) to X(64)	Displaced fluid content of the tube

X(65) to X(72)	Effective pressure drops across the tubes
X(73)	Incoming fluids
	1.0 displaced
	2.0 displacing
	3.0 Both
	4.0 none (node point isolated)
X(74)	Absolute pressure at node points
X(75) to X(82)	Appropriate conductivities of the tubes
X(83)	Volume of incoming displaced fluid
X(84)	Volume of incoming displacing fluid
X(85) to X(92)	Effective capillary pressures
X(93)	Provisional total outflow of displaced fluid
X(94)	Provisional total outflow of displacing fluid
X(95) to X(102)	Provisional inflow of displaced fluid in tubes
X(103) to X(110)	Provisional inflow of displacing fluid in tubes
X(111) to X(118)	Provisional outflow of displaced fluid from tubes
X(119) to X(126)	Provisional outflow of displacing fluid from tubes
IR	No. of rows in network
JR	No. of column in network
GAMA	Interfacial tension
THETA	Contact angle
RAD	Tube radius

COM	Cumulative distribution
GRID	Grid size
TRAP	Value of trapping factor
HYST	Hysteresis in contact angle (=0)
TIME	Time step
ISTAR-IFIN	No. of time steps for each pressure
AV	Displaced fluid content of the network
ICP	No. of pressure steps



## FORTRAN SOURCE LIST

## SOURCE STATEMENT

12/4/7

\$IBFTC CALC

COMMON/SYNARG/X(50,16),AP(50,8),GC,VO,VW,TIME,VDF(50,8),IJ,IR,JR,	3PP00002
1XA,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID	BPP00003
COMMON/PRESS/NN,A(50,50),AB(50)	BPP00004
COMMON/SOL/AA(50,50),BB(50),AV(40),WR(40),WO(40),WI(40),DEN(40)	BPP00005
COMMON/SOLB/CAP(1,10),I,ICHANG,ARAT,TRAP	BPP00006
COMMON/CHAN/DIFD,WDIF	BPP00007
COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFD(50,8),BASE	BPP00008
COMMON/SJLC/A00,CP,JIM,ICP	BPP00009
COMMON/SIM/COM(15),RAD(15),KL,LK	BPP00010
READ AND PRINT ALL THE RELEVANT INPUT DATA	BPP00011
CALL FLUN(99999)	BPP00012
DO 987 IKJ=1,2	BPP00013
READ 1,IR,JR,GAMMA,THETA,CP,VO,VW	BPP00014
PRINT 987	BPP00015
987 FORMAT(1H1)	BPP00016
PRINT 10,IK,JR,GAMMA,THETA,CP,VO,VW	BPP00017
READ 20,KL,LK	BPP00018
PRINT 30,IR,JR,KL,LK	BPP00019
READ 40,(COM(I),I=1,LK)	BPP00020
PRINT 40,(COM(I),I=1,LK)	BPP00021
READ 40,(RAD(J),J=1,LK)	BPP00022
PRINT 40,(RAD(J),J=1,LK)	BPP00023
PRINT 40,VO,VW,CP	BPP00024
READ 40,GRID	BPP00025
PRINT 40,GRID	BPP00026
READ 12,XA,HYST,TRAP	BPP00027
PRINT 12,XA,HYST,TRAP	BPP00028
READ 7,TIME	BPP00029
PRINT 7,TIME	BPP00030
READ 10,ISTAR,IFIN	BPP00031
PRINT 10,ISTAR,IFIN	BPP00032
I=ISTAR-1	BPP00033
READ 37,WR(I+1),DEN(I+1),STW,STO	BPP00034
IF(ISTAR.EQ.1)I=1	BPP00035
READ 37,AV(1),WO(1),WO(I),WI(I)	BPP00036
A00=WO(I)	BPP00037
7 FORMAT(1X,F15.10)	BPP00038
10 FORMAT(2I3,6F10.5)	BPP00039
11 FORMAT(20X,4I4)	BPP00040
12 FORMAT(8F10.5)	BPP00041
13 FORMAT(6F10.5)	BPP00042
14 FORMAT(12F10.5)	BPP00043
40 FORMAT(1X,8F10.5)	BPP00044
30 FORMAT(1X,2I8)	BPP00045
37 FORMAT(4X,8E12.5)	BPP00046
50 FORMAT(20X,15HOIL SATURATION=,F10.4,17HWATER SATURATION=,F10.4)	BPP00047
51 FORMAT(20X,7HTHE PT.,I4,25HIS BETWEEN 1AND 4 IN C73 )	BPP00048
52 FORMAT(20X,7HTHE PT.,I4,12HHAS 4 IN C73 )	BPP00049
100 FORMAT(//// 8(9X,1H ))	BPP00050
111 FORMAT(30X,21HPRESSURE DISTRIBUTION )	BPP00051
117 FORMAT(//1X,30X,18HFLUID DISTRIBUTION )	BPP00052
310 FORMAT(//20X,I4,7F13.5//)	BPP00053
759 FORMAT(20X,*CONTACT ANGLE=* F6.2,*DEGREES*)	BPP00054
760 FORMAT(20X,*VISCOSITY RATIO(OIL/WATER)=*,F6.2)	BPP00055

## SOURCE STATEMENT

751	FORMAT(1HL)	BPP00530
	N=IR*JR	BPP00540
	JIM=N-JR	BPP00550
	THETA IS CONTACT ANGLE AND GAMMA IS INTERFACIAL TENSION	BPP00560
	ARAT=VO/VW	BPP00570
	ARG=THETA*3.1416/180.	BPP00580
	GC=1.782*GAMMA*COS(ARG)/68947.31	BPP00590
	CAT=0.0	BPP00600
	PRINT 759, THETA	BPP00610
	READ DATA FROM TAPE	BPP00620
	CALL SIMU	BPP00630
	PRINT37, ((X(J,K),K=1,8),J=1,N)	BPP00640
	PRINT37, ((X(J,K),K=57,64),J=1,N)	BPP00650
	DO 20 IJ=1,N	BPP00660
	IK=IJ/JR+1	BPP00670
	JK=IJ-JR*(IK-1)	BPP00680
	IF(JK.LE.0)IK=IK-1	BPP00690
	IF(JK.LE.0)JK=JR	BPP00700
	EP(IK,JK)=X(IJ,74)	BPP00710
	CAP(IK,JK)=0.0	BPP00720
	DO 39 IA=1,8	BPP00730
	X(IJ,IA+16)=1.0	BPP00740
	X(IJ,IA+24)=1.0	BPP00750
	X(IJ,IA+136)=THETA	BPP00760
	IF(X(IJ,IA).EQ.0.0)X(IJ,IA+24)=2.0	BPP00770
	X(IJ,IA+40)=X(IJ,IA+32)*VO/VW	BPP00780
	X(IJ,IA+56)=X(IJ,IA+48)	BPP00790
	X(IJ,IA+74)=X(IJ,IA+32)	BPP00800
	X(IJ,IA+84)=0.0	BPP00810
	X(IJ,IA+94)=0.0	BPP00820
	X(IJ,IA+102)=0.0	BPP00830
	X(IJ,IA+110)=0.0	BPP00840
	X(IJ,IA+118)=0.0	BPP00850
39	CONTINUE	BPP00860
	X(IJ,83)=0.0	BPP00870
	X(IJ,84)=0.0	BPP00880
	X(IJ,93)=0.0	BPP00890
	X(IJ,73)=1.0	BPP00900
	X(IJ,94)=0.0	BPP00920
20	CONTINUE	BPP00930
	PRINT 12, GAMMA	BPP00940
	STW=0.0	BPP00950
	STO=0.0	BPP00960
	AV(1)=0.0	BPP00970
	DO 900 ICP=1,12	BPP00980
	WI(1)=0.0	BPP00981
	DO 900 ICP=1,10	BPP00982
	IF(ICP.GE.3)TIME=0.001	BPP00983
	IF(ICP.GE.5)TIME=0.005	BPP00990
	IF(ICP.GE.8)TIME=0.01	BPP01000
	READ7, CP	BPP01010
	PRINT7, CP	BPP01020
	DO 700 I=1STAR, IFIN	BPP01030
	IF(ICP.EQ.1) WO(1)=0.0	
	IF(ICP.EQ.1) WI(1)=0.0	

## SOURCE STATEMENT

## FORTRAN SOURCE LIST CALC

48	CONTINUE	BPP01040
	FRAME EXAMINE AND SOLVE THE SYSTEM OF EQUATIONS	BPP01050
	CALL SOLVE	BPP01060
	IF(ICP.LT.10) GO TO 107	3PP01061
108	PRINT 111	BPP01070
	PRINT PRESS DISTRIBUTION	BPP01080
	DO 107 IB=1,IR	3PP01090
	PRINT 109	BPP01100
	PRINT 14,(EP(13,JK),JK=1,JR)	BPP01110
107	CONTINUE	BPP01120
	PRINT 117	3PP01130
	A00=0.0	3PP01140
	AW0=0.0	BPP01150
	SWL=0.0	BPP01160
	IF(I.NE.1)SWL=1.0-AV(I)/AV(1)	3PP01170
	AV(I)=0.0	3PP01180
	ILK=0	BPP01190
	SATL=0.0	BPP01200
	SATO=0.0	3PP01210
	DO 300 KRS=1,N	3PP01220
	CALL POINTS IN PROPER SEQUENCE	BPP01230
	IF(KRS.LE.1LK) GO TO 300	BPP01240
	DO 305 K=KRS,N	3PP01250
	IK=K/JR+1	BPP01260
	JK=K-JR*(IK-1)	BPP01270
	IF(JK.LE.0)IK=IK-1	BPP01280
	IF(JK.LE.0)JK=JR	BPP01290
	IF(JK.EQ.JR)GO TO 320	BPP01300
	DPE=EP(IK,JK)-EP(IK,JK+1)+CAP(IK,JK)	BPP01310
	IF(DPE.GE.0.0)GO TO 320	3PP01320
305	CONTINUE	BPP01330
320	ILK=K	BPP01340
	MK=ILK-KRS+1	BPP01350
	DO 350 KR=1,MK	3PP01360
	IJ=ILK-KR+1	3PP01370
	J=IJ	BPP01380
	IF(ICP.LT.15)GO TO 2	BPP01381
	PRINT 10,IJ	3PP01390
2	CONTINUE	BPP01391
	IK=IJ/JR+1	BPP01400
	JK=IJ-JR*(IK-1)	BPP01410
	IF(JK.LE.0) IK=IK-1	BPP01420
	IF(JK.LE.0)JK=JR	BPP01430
	IJA=IJ	BPP01440
	M=1	BPP01450
	VWI=0.0	3PP01460
	VOI=0.0	BPP01470
	MMK=0	BPP01480
	BASE=0.0	BPP01490
	IF(X(J,73).EQ.4.0) GO TO 291	BPP01500
	COMPUTE FLOW RATES FOR OIL AND WATER INCOMING OUTGOING	BPP01510
	CALL FLOW	BPP01520
	VOI=X(J,83)	3PP01530
	VWI=X(J,84)	BPP01540
	IF(IK.EQ.1)VOI=0.0	BPP01550

## FORTRAN SOURCE LIST CALC

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## SOURCE STATEMENT

	IF(IK.EQ.1)VWI=0.0	BPP01560
	IF(IK.EQ.1)GO TO 214	BPP01570
C	UPDATE X(73)=LIQUIDS ENTERING THE JUNCTION POINT	BPP01580
	IF(VOI.EQ.0.0.AND.VWI.EQ.0.0)X(J,73)=4.0	BPP01590
	IF(VOI.EQ.0.0.AND.VWI.NE.0.0)X(J,73)=2.0	BPP01600
	IF(VOI.NE.0.0.AND.VWI.NE.0.0)X(J,73)=3.0	BPP01610
	IF(VOI.NE.0.0.AND.VWI.EQ.0.0)X(J,73)=1.0	BPP01620
	VOI=ABS(VOI)	BPP01620
	VWI=ABS(VWI)	BPP01620
	IF(IJ.GT.JIM)GO TO 291	BPP01630
C	COMPUTE OUT FLOWING VOLUMES	BPP01640
214	VVO=X(J,93)	BPP01650
	VWO=X(J,94)	BPP01660
	VVO=ABS(VVO)	BPP01670
	VWO=ABS(VWO)	BPP01680
	DELTA=VOI+VWI-VVO-VWO	BPP01690
	IF(VVO.LE.0.10E-10)VVO=0.0	BPP01700
	IF(VWO.LE.0.10E-10)VWO=0.0	BPP01710
	IF(VWI.LE.0.10E-10)VWI=0.0	BPP01720
	IF(VOI.LE.0.10E-10)VOI=0.0	BPP01730
	IF(ABS(DELTA).LE.0.1E-10) DELTA=0.0	BPP01740
	DELO=VOI-VVO	BPP01750
	DELOW=VWI-VWO	BPP01760
	DELO=ABS(DELO)	BPP01770
	DELOW=ABS(DELOW)	BPP01780
	IF(DELO.LT.0.1E-10)VVO=VOI	BPP01790
	IF(DELOW.LT.0.1E-10)VWO=VWI	BPP01800
	IF(ICP.LT.15)GO TO 1	BPP01801
888	PRINT37,VOI,VVO,VWI,VWO,DELTA	BPP01810
	IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=75,82)	BPP01820
	IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=65,72)	BPP01830
	IF(DELTA.NE.0.0)PRINT37,(X(J,KA+94),KA=1,32)	BPP01840
	IF(DELTA.EQ.0.0)PRINT37,(X(J,KA),KA=75,82)	BPP01841
	IF(DELTA.EQ.0.0)PRINT37,(X(J,KA),KA=65,72)	BPP01842
1	CONTINUE	BPP01850
C	UPDATE OIL CONTENT OF TUBES	BPP01851
	DO 21 K=1,8	BPP01852
	DEN(K)=X(J,K+56)	BPP01855
21	X(J,K+56)=VOF(J,K)	BPP01857
	DO 470 JP=1,8	BPP01860
	ICAN(J,JP)=0	BPP01870
	AWDIF(J,JP)=0.0	BPP01880
	ADIFD(J,JP)=0.0	BPP01890
	IF(X(J,JP+16).EQ.0.0)PRINT 11,IJ,JP	BPP01900
470	CONTINUE	BPP01910
	CASE=0.0	BPP01920
	IF(IK.NE.1.AND.VVO.EQ.0.0.AND.VWO.EQ.0.0)X(J,73)=4.0	BPP01930
	IF(IK.EQ.1.AND.VVO.EQ.0.0.AND.VOI.EQ.0.0.AND.VWO.EQ.0.0.AND.VWI.	BPP01940
	1EQ.0.0)X(J,73)=4.0	BPP01950
	IF(X(J,73).EQ.4.0) CASE=1.0	BPP01960
	IF(X(J,73).EQ.4.0) GO TO 270	BPP01970
C	COMPENSATE FOR IMBA ANCE IM INFLOW-OUTFLOW AT A POINT BY PICKING TUB	BPP01980
C	MONTE CARLO TECHNIQUE	BPP01990
	IF(IJ.LE.JR) CASE=1.0	BPP02000
	IF(IJ.LE.JR) GO TO 4805	BPP02010

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## SOURCE STATEMENT

	IF(VOI.GE.VDO.AND.VWI.GE.VWD)CASE=1.0	BPP02020
	IF(VOI.GE.VDO.AND.VWI.GE.VWD) GO TO 4805	BPP02030
	IF((VOI+VWI).LE.0.0) GO TO 4805	BPP02040
	WDIF=VWI-VWD-(DELTA*VWI)/(VOI+VWI)	3PP02050
	DIFO=VOI-VDO-(DELTA*VOI)/(VOI+VWI)	BPP02060
	IF(WDIF.LE.0.1E-10)WDIF=0.0	BPP02070
	IF(DIFO.LE.0.1E-10)DIFO=0.0	3PP02080
	IF(DIFO.LE.0.0.AND.WDIF.LE.0.0)GO TO 4805	3PP02090
	CALL CHANGE	BPP02100
	IF(DIFO.NE.0.0.OR.WDIF.NE.0.0)PRINT37,(X(J,KA+74),KA=1,8)	BPP02101
C	BASE.EQ.1.0 MEANS UPSTREAM DATA HAS TO BE CORRECTED DUE TO FLOW CH3	3PP02110
4805	DO 1003 K=1,8	BPP02120
	X(J,K+56)=DEN(K)	BPP02121
	X(J,K+16)=FLO(J,K)	BPP02130
	IF(X(J,K+24).GE.1.5)GO TO 1005	3PP02140
	IF(X(J,K+64).LE.0.0)GO TO 1005	3PP02150
	X(J,K+110)=X(J,K+94)+X(J,K+56)-VDF(J,K)	BPP02160
	X(J,K+118)=X(J,K+102)+VDF(J,K)-X(J,K+56)	BPP02170
	X(J,K+56)=VDF(J,K)	BPP02180
1005	CONTINUE	BPP02190
270	CAT=1.0	BPP02200
	CALL COND(1)	BPP02210
	CAT=0.0	BPP02220
	IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291	BPP02230
	IF(BASE.EQ.1.0) GO TO 479	BPP02240
	ICAN(J,M)=0	BPP02250
	GO TO 483	3PP02260
479	DO 481 ICA=6,8	BPP02270
	IF(BASE.EQ.1.0)PRINT 11,IJ,ICAN(J,1),ICAN(J,7),ICAN(J,8)	BPP02280
	IF(BASE.EQ.1.0)BASE=2.0	3PP02290
	M=ICA	3PP02300
	IF(ICA.EQ.6)M=1	BPP02310
	MMK=ICAN(J,M)	BPP02320
	ICAN(J,M)=0	3PP02330
	IF(MMK.EQ.0) GO TO 482	BPP02340
	WDIF=AWDIF(J,M)	BPP02350
	DIFO=ADIFO(J,M)	BPP02360
	IF(X(J,M+64).GT.0.0)CASE=2.0	3PP02361
	IF(CASE.LT.2.0)J=MMK	BPP02370
	IF(WDIF.LE.0.0.AND.DIFO.LE.0.0) GO TO 482	BPP02380
	DO 478 K=1,8	BPP02390
	FLO(J,K)=X(J,K+16)	3PP02400
	VDF(J,K)=X(J,K+56)	BPP02410
	AP(J,K)=0.0	BPP02420
	IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)	BPP02430
478	CONTINUE	3PP02440
430	IF(WDIF.LE.0.1E-10)WDIF=0.0	BPP02450
	IF(DIFO.LE.0.1E-10)DIFO=0.0	BPP02460
	IF(DIFO.LE.0.0.AND.WDIF.LE.0.0) GO TO 485	BPP02470
	CALL CHANGE	3PP02480
C	ENTER CHANGES IN VOL OUTFLOW/INFLOW,AND FLUID CONTENT	BPP02490
435	CONTINUE	BPP02500
486	DO 105 K=1,8	3PP02510
	X(J,K+56)=DEN(K)	BPP02511
	X(J,K+16)=FLO(J,K)	BPP02512

## FORTRAN SOURCE LIST CALC

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## SOURCE STATEMENT

1	IF(X(J,K+24).GE.1.5)GO TO 105	BPP02530
4	IF(X(J,K+64).LE.0.0)GO TO 105	BPP02540
7	X(J,K+110)=X(J,K+94)+X(J,K+56)-VOF(J,K)	3PP02550
0	X(J,K+118)=X(J,K+102)+VOF(J,K)-X(J,K+56)	3PP02560
1	X(J,K+56)=VOF(J,K)	BPP02570
2	105 CONTINUE	BPP02580
4	CAT=1.0	BPP02590
5	CALL COND(1)	BPP02600
6	CAT=0.0	BPP02610
7	IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291	BPP02620
2	IF(BASE.EQ.1.0) GO TO 479	3PP02630
5	ICAN(J,M)=0	BPP02640
6	482 CONTINUE	BPP02650
7	481 CONTINUE	BPP02660
1	483 BASE=0.0	3PP02670
2	MMK=0	BPP02680
3	J=IJA	BPP02690
4	291 IB=IJ+JR	BPP02700
5	DO 330 K=6,9	BPP02710
6	IA=K	BPP02720
7	IF(K.EQ.9) IA=1	BPP02730
2	AV(I)=AV(I)+X(J,IA+56)	BPP02740
3	IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT10,J,IA	3PP02741
6	IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT37,X(J,IA+48	BPP02742
1	1),X(J,IA+56)	BPP02743
3	330 CONTINUE	3PP02750
0	IF(I.EQ.1.AND.ICP.EQ.1)VOLPOR=AV(1)	BPP02760
3	C COMPUTE TOTAL OUTFLOW OF FLUIDS FROM THE SAMPLE	BPP02770
1	IF(VOI.LE.0.10E-10)VOI=0.0	BPP02780
4	IF(VWI.LE.0.10E-10)VWI=0.0	3PP02790
7	IF(IB.LE.N) GO TO 292	BPP02800
2	IF(ICP.LT.15)GO TO 3	BPP02801
3	PRINT 37,VOI,VWI	BPP02810
6	3 CONTINUE	3PP02811
7	ADD=ADD+VOI	BPP02820
0	AWO=AWO+VWI	BPP02830
3	DO 290 IA=7,9	BPP02840
6	K=IA	BPP02850
7	IF(K.EQ.9) K=1	BPP02860
0	SATL=SATL+X(J,K+56)	BPP02870
3	SATO=SATO+X(J,K+48)	3PP02880
6	290 CONTINUE	3PP02890
7	292 CONTINUE	BPP02900
0	C PRINT FLOW DISTRIBUTION	BPP02910
3	IF(ICP.LT.15)GO TO 4	BPP02911
6	PRINT37,(X(J,KA),KA=57,64)	3PP02913
7	777 PRINT12,(X(J,K),K=17,32)	BPP02920
0	IF(X(J,73).EQ.4.0) PRINT52,IJ	BPP02930
3	4 CONTINUE	BPP02931
6	IF(I.EQ.1.AND.ICP.EQ.1)GO TO 2222	BPP02940
7	GO TO 79	BPP02950
0	2222 CONTINUE	BPP02960
3	IF(IK.NE.1)GO TO 213	3PP02970
6	X(J,73)=2.	BPP02980
7	DO 212 K=3,5	BPP02990



## FORTRAN SOURCE LIST CALC

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## SOURCE STATEMENT

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      IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.0
212 CONTINUE
213 IF(IK.NE.2) GO TO 79
      DO 218 IA=7,9
      K=IA
      IF(K.EQ.9) K=1
      IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.5
218 CONTINUE
79 CONTINUE
      X(J,83)=0.0
      X(J,84)=0.0
      X(J,93)=0.0
      X(J,94)=0.0
      VOI=0.0
      VWI=0.0
296 CONTINUE
350 CONTINUE
300 CONTINUE
      PRINT 37, AV(I)
      SO=AV(I)/VOLPOR
      SW=1.0-SO
      PRINT 50, SO, SW
690 CONTINUE
      WI(I)=AWO
      WI(1)=WO(1)*ARAT
      CUML=(STO+STW)/AV(1)
      WO(I)=ADD
      STW=STW+WI(I)
      STO=STO+WO(I)
      PRINT 37, WO(1), WO(I), STO, STW, WI(I)
      W=WO(1)*0.01
      IF(I.GT.2.AND.ADD.LE.W) GO TO 800
700 CONTINUE
800 CONTINUE
900 CONTINUE
C  CALCULATE AND PRINT POROSITY AND PERMEABILITY
      AJR=JR
      AIR=IR
      POR=AV(1)/((AJR-1.)*(AIR-1.)*GRID**3)
      PERM=WI(1)*VW*(AIR-1.)/(TIME*GRID*(AJR-1.)*CP)
      PRINT 12, POR, PERM
      STOP
      END

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BPP03000
BPP03010
BPP03020
BPP03030
BPP03040
BPP03050
BPP03060
BPP03070
BPP03080
BPP03090
BPP03100
BPP03110
BPP03120
BPP03130
BPP03140
BPP03150
BPP03160
BPP03170
BPP03180
BPP03190
BPP03200
BPP03210
BPP03220
BPP03230
BPP03240
BPP03250
BPP03260
BPP03270
BPP03280
BPP03290
BPP03300
BPP03310
BPP03320
BPP03330
BPP03340
BPP03350
BPP03360
BPP03370
BPP03380
BPP03390
BPP03400
BPP03410
BPP03420

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IBMAP ASSEMBLY CALC

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ROR MESSAGES

T 307

ERROR 1311 ISN-221 DO VARIABLE REDEFINED IN ITS OWN RANGE.

VERITY WAS 0.



## FORTRAN SOURCE LIST

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## SOURCE STATEMENT

\$IBFTCSUB 1	3PP03430
SUBROUTINE SOLVE	BPP03440
COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VDF(50,8),IJ,IR,JR,	BPP03450
1XA ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID	BPP03460
COMMON/PRESS/NN,A(50,50),AB(50)	BPP03470
COMMON/SOL/AA(50,50),BB(50),AV(40),WR(40),WO(40),WI(40),DEN(40)	BPP03480
COMMON/SOLB/CAP(10,10),I,ICHANG,ARAT,TRAP	BPP03490
COMMON/SOLC/AQJ,CP,JIM,ICP	BPP03500
COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFD(50,8),BASE	BPP03510
INTEGER COUNT	BPP03520
10 FORMAT(2I3)	BPP03530
12 FORMAT(8F10.5)	BPP03540
50 FORMAT(20X,15HOIL SATURATION=,F10.4,17HWATER SATURATION=,F10.4)	BPP03550
750 FORMAT(20X,*VISCOSITY RATIO(OIL/WATER)=*,F6.2)	BPP03560
C FRAME SYSTEM OF EQUATIONS	BPP03570
BASE=0.0	BPP03580
N=IR*JR	BPP03590
NN=JR*(IR-2)	BPP03600
IS=JR+1	BPP03610
IT=N-JR	BPP03620
AV(I)=0.0	BPP03630
IC=0	BPP03640
30 CONTINUE	BPP03650
COUNT=0	BPP03660
IC=IC+1	BPP03670
IF(IC.EQ.1) PRINT 760,ARAT	BPP03680
DO 65 IJK=1,N	BPP03690
IJ=IJK	BPP03700
J=IJ	BPP03710
BB(IJK)=0.0	BPP03720
C FILLIN PROPER CONDUCTIVITIES	BPP03730
CAT=IC	BPP03740
IF(IC.EQ.1)CALL COND(2)	BPP03750
DO 65 JJK=1,N	BPP03760
55 AA(IJK,JJK)=0.0	BPP03770
195 DO 85 IJ=1,N	BPP03780
K=IJ	BPP03790
IK=IJ/JR+1	BPP03800
JK=IJ-JR*(IK-1)	BPP03810
IF(JK.LE.0) IK=IK-1	BPP03820
IF(JK.LE.0)JK=JR	BPP03830
CAP(IK,JK)=0.0	BPP03840
C READ (X(IJ,M),M=1,160)	BPP03850
CO=0.0	BPP03860
VS=0.0	BPP03870
CPT=0.0	BPP03880
IF(I.EQ.1.AND.IC.EQ.1.AND.ICP.EQ.1) GO TO 87	BPP03890
C COMPUTE OIL AND WATER SATURATION	BPP03900
IJK=IJ	BPP03910
215 DO 30 K2=1,4	BPP03920
AV(I)=AV(I)+X(IJK,K2+56)	BPP03930
30 CONTINUE	BPP03940
88 CONTINUE	BPP03950
IF(IC.EQ.1) GO TO 87	BPP03960
C FILL DELP FOR ALL POINTS 65-72	BPP03970

## FORTRAN SOURCE LIST UB 1

12/14/

## SOURCE STATEMENT

0	CALL PDIF	BPP03980
C	AVOID INFLOW FROM OUTLET END OR FROM INLET END .TRAP APPROPRIATE	TBPP03990
C	UBES	BPP04000
1	K=IJ	BPP04010
2	DO 76 KL=2,5	3PP04020
3	IF(K.GT.JIM) GO TO 76	3PP04030
6	COL=0.0	BPP04040
7	IJK=IJ	BPP04050
0	IF(X(IJK,KL+24).GE.1.5) GO TO 76	3PP04060
3	AS=0.0	3PP04070
4	IF(K.GT.NN.AND.K.LE.JIM) AS=1.0	BPP04080
7	IF(AS.EQ.1.0.AND.X(IJK,KL+64).LT.0.0) AS=2.0	BPP04090
2	IF(AS.EQ.2.0.AND.KL.GE.3.AND.KL.LE.5)COL=0.5	3PP04100
5	IF(K.LE.JR.AND.X(IJK,KL+64).LT.0.0) COL=0.5	BPP04110
0	IF(X(IJK,KL+16).LE.2.0) GO TO 55	3PP04120
3	IF(X(IJK,KL+16).GT.4.0)GO TO 55	3PP04130
6	IF(K.LE.JR) GO TO 55	BPP04140
1	DP=0.0	BPP04150
2	DP=X(IJK,KL+84)	3PP04160
3	DP=DP*(1.+TRAP)	3PP04161
4	ADP=X(IJK,KL+64)-X(IJK,KL+84)	3PP04170
5	IF(DP.LE.0.0.AND.ADP.LE.0.0) GO TO 55	BPP04180
0	IF(ADP.GE.0.0.AND.DP.GE.0.0) GO TO 55	BPP04190
3	DP=ABS(DP)	3PP04200
4	ADP=ABS(ADP)	3PP04210
5	IF(ADP.LT.DP) COL=0.5	BPP04220
0	55 IF(COL.EQ.0.5) X(IJK,KL+24)=1.5	BPP04230
3	IF(COL.EQ.0.5) CO=0.5	BPP04250
6	76 CONTINUE	BPP04260
0	IF(CO.EQ.0.0) GO TO 77	BPP04270
3	CAT=0.0	BPP04280
4	COUNT=COUNT+1	3PP04300
5	J=IJ	BPP04310
6	CALL COND(1)	BPP04320
7	77 CONTINUE	3PP04330
0	87 CONTINUE	3PP04340
1	DO 82 IL=1,8	BPP04350
2	IF(X(IJ,73).EQ.4.0) GO TO 82	3PP04360
5	IF(X(IJ,IL+24).GE.1.5) GO TO 82	BPP04370
0	CPA=X(IJ,IL+84)	BPP04380
1	CPT=CPT+X(IJ,IL+74)*CPA	BPP04390
2	VS=VS+X(IJ,IL+74)	BPP04400
3	IF(IL.EQ.2) CAP(IK,JK)=CPA	3PP04410
6	82 CONTINUE	BPP04420
0	IF(VS.EQ.0.0) GO TO 85	BPP04430
3	IF(IJ.LT.IS.OR.IJ.GT.IT) GO TO 85	BPP04440
5	VA=0.0	3PP04450
7	DO 70 K=1,8	BPP04460
0	X(IJ,K+94)=0.0	BPP04470
1	X(IJ,K+102)=0.0	BPP04480
2	X(IJ,K+110)=0.0	3PP04490
3	X(IJ,K+118)=0.0	BPP04500
4	IA=IK	BPP04510
5	JA=JK	BPP04520
6	IF(K.EQ.1) IA=IK-1	BPP04530

## FORTRAN SOURCE LIST UB 1

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## SOURCE STATEMENT

1	IF(K.LE.3) JA=JK+1	3PP0454
4	IF(K.GE.5.AND.K.LE.7) JA=JK-1	BPP0455
7	IF(K.GE.3.AND.K.LE.5) IA=IK+1	BPP0456
2	IF(K.GE.7) IA=IK-1	BPP0457
5	IJC=(IA-1)*JR+JA	BPP0458
6	AA(IJ,IJC)=-X(IJ,K+74)	3PP0459
7	IF(IJC.LE.JR) VA=VA+AA(IJ,IJC)*CP	BPP0460
2	70 CONTINUE	BPP0461
4	BB(IJ)=-VA-CPT	3PP0462
5	35 AA(IJ,IJ)=VS	BPP0463
6	86 CONTINUE	3PP0464
0	IF(IC.NE.1.AND.COUNT.EQ.0) GO TO 78	BPP0465
3	DO 66 IN=1,NN	BPP0466
4	INR=IN+JR	BPP0467
5	AB(IN)=BB(INR)	3PP0468
6	DO 66 JN=1,NN	BPP0469
7	JNR=JN+JR	BPP0470
0	A(IN,JN)=AA(INR,JNR)	BPP0471
1	66 CONTINUE	BPP0472
4	CALL PRSOL(1)	BPP0473
5	CALL PRSOL(2)	BPP0474
6	DO 75 K=1,N	BPP0475
7	BB(K)=CP	3PP0476
0	IF(K.GT.JIM) BB(K)=0.	BPP0477
3	IF(K.LE.JR.OR.K.GT.JIM) GO TO 73	BPP0478
6	KK=K-JR	BPP0479
7	BB(K)=AB(KK)	BPP0480
0	73 IK=K/JR+1	BPP0481
1	JK=K-JR*(IK-1)	BPP0482
2	IF(JK.EQ.0) IK=IK-1	BPP0483
5	IF(JK.EQ.0) JK=JR	3PP0484
0	EP(IK,JK)=BB(K)	3PP0485
1	75 CONTINUE	BPP0486
3	78 CONTINUE	3PP0487
4	PRINT 10,COUNT	BPP0488
5	IF(COUNT.NE.0) GO TO 80	BPP0489
0	IF(IC.EQ.1) GO TO 80	BPP0490
3	RETURN	3PP0491
4	END	BPP0492

IBMAP ASSEMBLY UB 1

12/04/

MESSAGES FOR ABOVE ASSEMBLY

## FORTRAN SOURCE LIST

12/04/

## SOURCE STATEMENT

0	\$IBFTCSUB		BPP04937
1	SUBROUTINE PRSDL(KKK)		BPP04940
2	COMMON/PRESS/NN,A(50,50),AB(50)		BPP04950
3	GO TO (1000,2000),KKK		BPP04960
C	REDUCE MATRIX BY GAUSS ELIMINATION PROCEDURE		BPP04970
4	1000 N=NN+1		BPP04980
5	DO 230 J=1,NN		BPP04990
6	A(I,N)=-AB(I)		BPP05000
7	230 CONTINUE		BPP05010
1	DO 282 L=1,NN		BPP05020
2	M=L+1		BPP05030
3	IF(M.GT.NN) GO TO 282		BPP05040
6	DO 281 I=M,NN		BPP05050
7	IF(A(L,L).EQ.0.0) GO TO 281		BPP05060
2	C=A(I,L)/A(L,L)		BPP05070
3	IF(C.EQ.0.0) GO TO 281		BPP05080
6	DO 280 J=1,N		BPP05090
7	IF(A(L,J).EQ.0.0) GO TO 280		BPP05100
2	Z=C*A(L,J)		BPP05110
3	A(I,J)=A(I,J)-Z		BPP05120
4	280 CONTINUE		BPP05130
6	281 CONTINUE		BPP05140
0	282 CONTINUE		BPP05150
2	DO 340 L=1,NN		BPP05160
3	I=N-L		BPP05170
4	C=A(I,I)		BPP05180
5	DO 320 J=1,N		BPP05190
6	IF(C.EQ.0.0) GO TO 320		BPP05200
1	IF(A(I,J).EQ.0.0) GO TO 320		BPP05210
4	A(I,J)=A(I,J)/C		BPP05220
5	320 CONTINUE		BPP05230
7	BA=A(I,N)		BPP05240
0	IA=I-1		BPP05250
1	IF(IA.EQ.0) GO TO 340		BPP05260
4	IF(BA.EQ.0.0) GO TO 340		BPP05270
7	DO 330 IB=1,IA		BPP05280
0	A(IB,N)=A(IB,N)-BA*A(IB,I)		BPP05290
1	330 A(IB,I)=0.0		BPP05300
3	340 CONTINUE		BPP05310
5	GO TO 500		BPP05320
6	2000 DO 450 I=1,NN		BPP05330
7	450 AB(I)=-A(I,N)		BPP05340
1	500 RETURN		BPP05350
2	END		BPP05360

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MESSAGES FOR ABOVE ASSEMBLY

## FORTRAN SOURCE LIST

## SOURCE STATEMENT

\$IBFTCSUB 3	BPP0507
SUBROUTINE FLOW	BPP0508
COMMON/SYMARO/X(50,160),AP(50,8),GC,VO,VW,TIME,VDF(50,8),IJ,IR,JR,	BPP0509
1XA,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID	BPP0540
C FLOW CAPACITY OF TUBES	BPP0541
ARAT=VO/VW	BPP0542
N=IR*JR	BPP0543
IB=N-2*JR	BPP0544
X(J,93)=0.	BPP0545
X(J,94)=0.0	BPP0546
DO 200 K=1,8	BPP0547
VDF(J,K)=X(J,K+56)	BPP0548
AP(J,K)=0.	BPP0549
IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)	BPP0550
X(J,K+94)=0.0	BPP0551
X(J,K+102)=0.0	BPP0552
X(J,K+110)=0.0	BPP0553
X(J,K+118)=0.0	BPP0554
IF(X(J,73).EQ.4.0) GO TO 200	BPP0555
C CASE 2.0 MEANS BACK FLOW	BPP0556
CASE=0.0	BPP0557
FLO(J,K)=X(J,K+16)	BPP0558
IF(K.GE.3.AND.K.LE.5)CASE=1.0	BPP0559
IF(CASE.EQ.1.0.AND.AP(J,K).EQ.0.0) CASE=2.0	BPP0560
IF(CASE.EQ.2.0)AP(J,K)=X(J,K+64)	BPP0561
IF(X(J,K+24).GE.2.0)GO TO 200	BPP0562
VA=AP(J,K)*X(J,K+74)	BPP0563
VA=VA*TIME	BPP0564
VA=ABS(VA)	BPP0565
IF(VA.EQ.0.0)GO TO 200	BPP0566
IF(CASE.EQ.2.0) GO TO 5	BPP0567
GO TO 7	BPP0568
5 IF(X(J,K+16).EQ.4.2) FLO(J,K)=4.2	BPP0569
IF(X(J,K+16).EQ.4.1) FLO(J,K)=4.1	BPP0570
IF(X(J,K+16).EQ.3.0)FLO(J,K)=3.5	BPP0571
IF(X(J,K+16).EQ.3.5)FLO(J,K)=3.0	BPP0572
7 IF(FLO(J,K).LE.2.0) GO TO 10	BPP0573
IF(FLO(J,K).LT.4.0.AND.FLO(J,K).GE.3.0)GO TO 20	BPP0574
IF(FLO(J,K).GE.4.0) GO TO 30	BPP0575
10 IF(FLO(J,K).EQ.1.0) X(J,K+94)=VA	BPP0576
IF(FLO(J,K).EQ.2.0) X(J,K+102)=VA	BPP0577
GO TO 90	BPP0578
20 IF(FLO(J,K).EQ.3.5) X(J,K+94)=VA	BPP0579
IF(FLO(J,K).EQ.3.0) X(J,K+102)=VA	BPP0580
GO TO 80	BPP0581
30 IF(FLO(J,K).EQ.4.5) GO TO 40	BPP0582
IF(FLO(J,K).EQ.4.1) X(J,K+94)=VA	BPP0583
IF(FLO(J,K).EQ.4.2) X(J,K+102)=VA	BPP0584
SD=X(J,K+56)/X(J,K+48)	BPP0585
SW=1.-SD	BPP0586
AKRW=X(J,K+40)*(2.*SW/ARAT+SW*SW*(1.-2.0/ARAT))	BPP0587
AKRN=X(J,K+32)*SD*SD	
AAK=AKRW/VW+AKRN/VO	
AKRW=AKRW*X(J,K+74)/AAK/VW	
AKRN=AKRN*X(J,K+74)/AAK/VO	

## SOURCE STATEMENT

	X(J,K+94)=ABS(AKRN*AP(J,K)*TIME )	BPP05835
	X(J,K+102)=ABS(AKRW*AP(J,K)*TIME )	BPP05839
	GO TO 80	BPP05840
40	SD=VDF(J,K)/X(J,K+48)	BPP05850
	SW=1.0-SD	BPP05860
	VWET=VW	BPP05870
	VNW=VJ	BPP05880
	SWET=SW	BPP05890
	SNW=SD	BPP05900
	IF(GC.LT.0.0)SWET=SD	BPP05910
	IF(GC.LT.0.0)SNW=SW	BPP05920
	IF(GC.LT.0.0) VNW=VW	BPP05930
	IF(GC.LT.0.0) VWET=VJ	BPP05940
	RWET=SWET*SWET	BPP05950
	RNW=2.0*VNW*SNW+SNW*SNW*(1.0-2.0*VNW/VWET)	BPP05960
	TOT= RWET/VWET+RNW/VNW	BPP05970
	RAW=RWET/VWET/TOT	BPP05980
	RAN=RNW/VNW/TOT	BPP05990
	IF(SW.EQ.SWET) RW=RAW	BPP06000
	IF(SW.EQ.SWET) RD=RAN	BPP06010
	IF(SW.EQ.SNW)RW=RAN	BPP06020
	IF(SW.EQ.SNW) RD=RAW	BPP06030
	X(J,K+94)=RD*VA	BPP06040
	X(J,K+102)=RW*VA	BPP06050
80	VOMAX=X(J,K+48)	BPP06070
	VOMIN=0.0	BPP06080
	IF(GC.GT.0.0) VOMAX=0.96*X(J,K+48)	BPP06090
	IF(GC.LT.0.0)VOMIN=0.04*X(J,K+48)	BPP06100
	IF(VOMAX.LT.VDF(J,K))VOMAX=X(J,K+48)	BPP06110
	IF(VOMIN.GT.VDF(J,K))VOMIN=0.0	BPP06120
	VWMAX=X(J,K+48)-VOMIN	BPP06130
	VWMIN=X(J,K+48)-VOMAX	BPP06140
	IF(FLO(J,K).GT.4.0)GO TO 83	BPP06141
	IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.3.0) GO TO 85	BPP06150
	V=VA+VDF(J,K)	BPP06160
	IF(V.GT.VOMAX) GO TO 82	BPP06170
	VDF(J,K)=VDF(J,K)+VA	BPP06180
	X(J,K+110)=0.0	BPP06190
	X(J,K+118)=VA	BPP06200
	IF(GC.GT.0.0)FLO(J,K)=4.5	BPP06201
	GO TO 100	BPP06210
82	CONTINUE	BPP06220
	X(J,K+110)=V-VOMAX	BPP06230
	X(J,K+118)=VOMAX-VDF(J,K)	BPP06240
	VDF(J,K)=VOMAX	BPP06241
	FLO(J,K)=1.0	BPP06250
	GO TO 100	BPP06260
85	V=VA+X(J,K+48)-VDF(J,K)	BPP06270
	IF(V.GT.VWMAX) GO TO 86	BPP06280
	VDF(J,K)=VDF(J,K)-VA	BPP06290
	X(J,K+110)=VA	BPP06300
	X(J,K+118)=0.0	BPP06310
	GO TO 100	BPP06320
86	CONTINUE	BPP06330
	X(J,K+110)=VDF(J,K)-VOMIN	BPP06340

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## SOURCE STATEMENT

1	X(J,K+118)=VA-X(J,K+110)	BPP06350
2	VDF(J,K)=VDMIN	3PP06351
3	FLO(J,K)=2.0	BPP06360
4	GO TO 100	BPP06370
5	33 V=VDF(J,K)-VDMIN	BPP06371
6	IF(V.LT.X(J,K+94))GO TO 84	BPP06372
1	VDF(J,K)=VDF(J,K)-X(J,K+94)	3PP06373
2	GO TO 90	BPP06374
3	34 X(J,K+94)=VDF(J,K)-VDMIN	BPP06375
4	X(J,K+102)=VA-X(J,K+94)	3PP06376
5	VDF(J,K)=VDMIN	BPP06377
6	FLO(J,K)=2.0	BPP06378
7	90 X(J,K+110)=X(J,K+94)	BPP06380
0	X(J,K+118)=X(J,K+102)	3PP06390
1	100 IF(CASE.EQ.2.0) GO TO 150	BPP06400
4	X(J,93)=X(J,93)+X(J,K+94)	BPP06410
5	X(J,94)=X(J,94)+X(J,K+102)	BPP06420
6	GO TO 200	3PP06430
7	150 CONTINUE	BPP06431
0	X(J,K+94)=X(J,K+110)	BPP06440
1	X(J,K+102)=X(J,K+118)	BPP06441
2	X(J,83)=X(J,83)+X(J,K+110)	BPP06442
3	X(J,84)=X(J,84)+X(J,K+118)	BPP06450
4	IF(IJ.LE.JR) X(J,K+24)=2.0	BPP06460
7	IF(IJ.GT.IB) X(J,K+24)=2.0	BPP06470
2	IF(X(J,K+24).EQ.2.0) X(J,K+74)=0.0	3PP06480
5	IF(X(J,K+24).EQ.2.0) X(J,K+84)=0.0	BPP06490
0	IF(X(J,K+24).EQ.2.0) X(J,K+24)=1.5	BPP06500
3	X(J,K+110)=0.0	3PP06510
4	X(J,K+118)=0.0	3PP06520
5	200 CONTINUE	BPP06530
7	RETURN	BPP06540
0	END	3PP06550

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## FORTRAN SOURCE LIST

## SOURCE STATEMENT

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\$IBFTCSUB 4		BPP06560
SUBROUTINE COND(KKK)		BPP06570
COMMON/SYMRG/X(50,16),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,		BPP06580
1 XA,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID		BPP06590
COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFO(50,8),BASE		BPP06600
GO TO (270,79),KKK		BPP06610
C ENTER CHANGES IN OTHER CONNECTED NODE POINTS		BPP06620
270 CONTINUE		BPP06630
11 FORMAT(20X,413)		BPP06640
13 FORMAT(10X,8F13.5)		BPP06650
N=IR*JR		BPP06660
JIM=N-JR		BPP06670
VS=0.0		BPP06680
IF(BASE.EQ.2.0)VS=1.0		BPP06690
DO 280 M=1,8		BPP06700
IF(X(J,M+24).EQ.1.5) GO TO 300		BPP06710
IF(JIM.LT.IJ) GO TO 273		BPP06720
IF(X(J,M+64).LE.0.0) GO TO 280		BPP06730
273 IF(X(J,M+24).GE.2.0) GO TO 280		BPP06740
300 CONTINUE		BPP06750
IF(X(J,M).EQ.0.0) GO TO 280		BPP06760
NX=M+4		BPP06770
IF(NX.GT.8) NX=M-4		BPP06780
MMK=IJ+JR-M+4		BPP06790
IF(M.EQ.1) MMK=IJ-JR+1		BPP06800
IF(M.EQ.2) MMK=IJ+1		BPP06810
IF(M.EQ.6) MMK=IJ-1		BPP06820
IF(M.EQ.7) MMK=IJ-JR-1		BPP06830
IF(M.EQ.8) MMK=IJ-JR		BPP06840
IF(MMK.GT.N) GO TO 280		BPP06850
IF(MMK.LE.0) GO TO 280		BPP06860
X(MMK,NX+56)=X(J,M+56)		BPP06870
X(MMK,NX+16)=X(J,M+16)		BPP06880
IF(X(J,M+16).EQ.4.1) X(MMK,NX+16)=4.1		BPP06890
IF(X(J,M+16).EQ.4.2) X(MMK,NX+16)=4.2		BPP06900
IF(X(J,M+16).EQ.3.5) X(MMK,NX+16)=3.0		BPP06910
IF(X(J,M+16).EQ.3.0) X(MMK,NX+16)=3.5		BPP06920
IF(X(J,73).EQ.4.0) X(MMK,NX+24)=2.0		BPP06930
IF(X(J,73).EQ.4.0) X(J,M+24)=2.0		BPP06940
IF(X(MMK,73).EQ.4.0) GO TO 275		BPP06950
IF(X(J,M+24).EQ.1.5) X(MMK,NX+24)=2.0		BPP06960
IF(X(J,M+24).EQ.1.5) X(J,M+24)=2.0		BPP06970
IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+74)=0.0		BPP06980
IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+84)=0.0		BPP06990
IF(X(MMK,NX+24).EQ.2.0) X(J,M+74)=0.0		BPP07000
IF(X(MMK,NX+24).EQ.2.0) X(J,M+84)=0.0		BPP07010
IF(X(MMK,NX+24).EQ.2.0) GO TO 275		BPP07020
274 IF(CAT.NE.1.0) GO TO 275		BPP07030
IF(X(J,M+24).EQ.1.5)X(MMK,NX+24)=2.0		BPP07040
IF(X(J,M+24).EQ.1.5)X(J,M+24)=2.0		BPP07050
IF(VS.NE.0.0) GO TO 275		BPP07060
IF(M.EQ.1.OR.M.GE.7) GO TO 272		BPP07070
X(MMK,83)=X(MMK,83)+X(J,M+110)		BPP07080
X(MMK,84)=X(MMK,84)+X(J,M+118)		BPP07090
GO TO 275		BPP07100



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272	CONTINUE	BPP07120
	IF(X(J,M+16).EQ.3.0.OR.X(J,M+16).EQ.3.5) GO TO 275	BPP07121
	IF(X(J,M+110).NE.X(MMK,NX+94)) ADIFD(J,M)=X(J,M+110)-X(MMK,NX+94)	BPP07130
	IF(X(J,M+118).NE.X(MMK,NX+102)) AWDIF(J,M)=X(J,M+118)-X(MMK,NX+	BPP07140
	1102)	BPP07150
	IF(ADIFD(J,M).NE.0.0.AND.AWDIF(J,M).NE.0.0) BASE=1.0	BPP07160
	X(MMK,NX+94)=X(J,M+110)	BPP07170
	X(MMK,NX+102)=X(J,M+118)	BPP07180
	IF(BASE.EQ.1.0) ICAN(J,M)=MMK	BPP07190
	IF(BASE.EQ.1.0) PRINT 13,X(J,M+74),X(J,M+64),X(J,M+16),X(MMK,NX+74),	BPP07200
	1X(MMK,NX+64),X(MMK,NX+16)	BPP07210
	IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0) PRINT 11,1J,MMK,ICAN(J,M)	BPP07220
	IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0) PRINT 13,X(J,M+110),X(J,M+118,	BPP07230
	1),X(J,M+94),X(J,M+102)	BPP07240
275	CONTINUE	BPP07250
280	CONTINUE	BPP07260
	GO TO 500	BPP07270
C	FILL PROPER CONDUCTIVITIES	BPP07280
79	DO 78 K=1,8	BPP07290
	BASE=0.0	BPP07300
	IF(X(J,K).EQ.0.0) GO TO 78	BPP07310
	IF(CAT.EQ.1.0) X(J,K+24)=1.0	BPP07320
	IF(X(J,73).EQ.4.0) X(J,73)=3.0	BPP07330
	SO=X(J,K+56)/X(J,K+48)	BPP07340
	SW=1.0-SO	BPP07350
	IF(X(J,K+16).EQ.1.0) X(J,K+74)=X(J,K+32)	BPP07360
	IF(X(J,K+16).EQ.2.0) X(J,K+74)=X(J,K+40)	BPP07370
	IF(X(J,K+16).EQ.1.0.OR.X(J,K+16).EQ.2.0) GO TO 830	BPP07380
	IF(X(J,K+16).NE.4.5) GO TO 821	BPP07390
	VL=VO	BPP07400
	IF(VW.GT.VL) VL=VW	BPP07410
	X(J,K+74)=X(J,K+32)*VO/(VO*SO+VW*SW+6.0*VL*X(J,K))	BPP07420
	GO TO 830	BPP07430
821	IF(X(J,K+16).EQ.3.0.OR.X(J,K+16).EQ.3.5) GO TO 822	BPP07440
	GO TO 823	BPP07450
822	X(J,K+74)=X(J,K+32)*VO/(VO*SO+VW*SW)	BPP07460
	GO TO 830	BPP07470
823	ARAT=VO/VW	BPP07480
	IF(GC.GE.0.0) GO TO 824	BPP07490
	IF(GC.LT.0.0) GO TO 825	BPP07500
824	AKRW=SW*SW*X(J,K+40)	BPP07510
	AKRN=X(J,K+32)*(2.0*SO*ARAT+SO*SO*(1.0-2.0*ARAT))	BPP07520
	TOT=AKRW/VW+AKRN/VO	BPP07530
	X(J,K+74)=X(J,K+32)*VO*TOT	BPP07531
	GO TO 830	BPP07540
825	AKRW=X(J,K+40)*(2.0*SW/ARAT+SO*SO*(1.0-2.0/ARAT))	BPP07550
	AKRN=X(J,K+32)*SO*SO	BPP07560
	TOT=AKRW/VW+AKRN/VO	BPP07570
	X(J,K+74)=TOT*VO*X(J,K+32)	BPP07571
830	CONTINUE	BPP07580
	X(J,K+74)=ABS(X(J,K+74))	BPP07590
	X(J,K+110)=0.0	BPP07600
	X(J,K+118)=0.0	BPP07610
	X(J,K+84)=0.0	BPP07620
	X(J,83)=0.0	BPP07630

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SOURCE STATEMENT

21	X(J,84)=0.0	3PP07640
22	IK=J/JR+1	BPP0765
23	JK=J-JR*(IK-1)	BPP0766
24	IF(JK.LE.0)IK=IK-1	3PP07670
27	IF(JK.LE.0)JK=JR	BPP0768
2	IF(IK.EQ.1)GO TO 140	3PP0769
5	IF(IK.EQ.2.AND.K.EQ.1)GO TO 140	BPP0770
7	IF(IK.EQ.2.AND.K.GE.7)GO TO 140	BPP07710
3	R=GC*((1.0/AA)-(1.0/X(J,K)))	3PP0772
4	R=-R	3PP0773
5	GO TO 150	BPP07740
6	140 R=GC/X(J,K)	BPP07750
7	150 CONTINUE	BPP0776
0	IF(X(J,K+16).EQ.3.0) X(J,K+84)= R	BPP0777
3	IF(X(J,K+16).EQ.3.5) X(J,K+84)=-R	BPP07780
6	78 CONTINUE	3PP07790
0	500 RETURN	3PP0780
1	END	BPP07810

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## FORTRAN SOURCE LIST

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SV	SOURCE STATEMENT	
0	\$IBFTCSUB 5	BPP07820
1	SUBROUTINE CHANGE	BPP07830
2	COMMON/SYMARG/X(50,160),AP(50,8),3C,VD,VW,TIME,VDF(50,8),IJ,IR,JR,	BPP07840
3	1XA,EP(10,10),HYST,CAT,GAMMA,J,FLD(50,8),GRID	BPP07850
4	COMMON/CHAN/DIFO,WDIF	BPP07860
5	COMMON/SOLB/CAP(10,10),I,ICHANG,ARAT,TRAP	BPP07861
6	COMMON/SOLC/ADD,CP,JIM,ICP	BPP07862
7	DIMENSION B(9),C(8)	BPP07870
8	REAL KA	BPP07880
9	590 FORMAT(2X,5HDIPO=,E13.5,5X,5HWDIF=,E13.5)	BPP07890
10	1F(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,DIFO,WDIF	BPP07891
11	4F(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=17,24)	BPP07892
12	3F(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=75,82)	BPP07893
13	2F(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K+94),K=1,32)	BPP07894
14	580 FORMAT(1X,8E15.7)	BPP07895
15	DO 550 K=1,8	BPP07900
16	C SELECT TUBES FOR FLOW CHANGES SO THAT MATERIAL BALANCE FOR EACH PH	BPP07910
17	C IS SATISFIED IN EACH NODE OF THE MODEL	BPP07920
18	3 C(K)=0.0	BPP07930
19	4 550 CONTINUE	BPP07940
20	C ETTING FLUID IMBIBITION	BPP07950
21	6 BASE=0.0	BPP07960
22	7 KA=0.0	BPP07970
23	0 CAT=0.0	BPP07980
24	1 ACE=0.0	BPP07981
25	2 IF(GC.GE.0.0.AND.WDIF.GT.0.0) KA=1.0	BPP07990
26	5 IF(GC.LT.0.0.AND.DIFO.GT.0.0) KA=2.0	BPP08000
27	0 IF(KA.EQ.0.0)KA=4.5	BPP08010
28	3 IF(KA.EQ.4.5) CAT=0.3	BPP08020
29	6 554 B(1)=0.0	BPP08030
30	7 DO 555 K=1,8	BPP08040
31	0 V=0.0	BPP08050
32	1 IF(X(J,K+24).GE.2.0)GO TO 555	BPP08060
33	4 IF(C(K).NE.0.0) GO TO 555	BPP08070
34	7 IF(FLD(J,K).NE.KA) GO TO 555	BPP08080
35	2 IF(AP(J,K).LE.0.0) GO TO 555	BPP08081
36	5 V=AP(J,K)*X(J,K+74)	BPP08090
37	6 V=ABS(V)	BPP08100
38	7 555 B(K+1)=B(K)+V	BPP08110
39	1 556 CONTINUE	BPP08120
40	2 IF(B(9).EQ.0.0) GO TO 559	BPP08130
41	5 RN=RNDY1(0.)	BPP08140
42	6 DO 557 K=2,9	BPP08150
43	7 IF(RN.LE.B(K)/B(9)) GO TO 558	BPP08160
44	2 557 CONTINUE	BPP08170
45	4 558 K=K-1	BPP08180
46	5 C(K)=1.0	BPP08190
47	6 GO TO 570	BPP08200
48	C PENDULAR FLOW CHANGE	BPP08210
49	7 559 IF(CAT.GE.0.3) GO TO 560	BPP08220
50	2 KA=4.5	BPP08230
51	3 CAT=0.3	BPP08240
52	4 GO TO 554	BPP08250
53	5 560 IF(CAT.EQ.0.3) GO TO 561	BPP08260
54	0 IF(CAT.EQ.0.4) GO TO 562	BPP08270

## FORTRAN SOURCE LIST UB 5

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## SOURCE STATEMENT

	IF(CAT.EQ.0.5) GO TO 563	BPP08250
	IF(CAT.EQ.0.6) GO TO 564	BPP08261
	IF(CAT.EQ.0.8) GO TO 565	BPP08262
	GO TO 620	BPP08290
561	CONTINUE	BPP08300
C	SLUG FLOW CHANGE	BPP08310
	IF(WDIF.GT.0.0) KA=4.2	BPP08320
	IF(DIFD.GT.0.0) KA=4.2	BPP08330
	CAT=.4	BPP08340
	GO TO 554	BPP08350
565	IF(WDIF.GT.0.0) KA=4.1	BPP08361
	IF(DIFD.GT.0.0) KA=4.1	BPP08362
	CAT=.3	BPP08363
	GO TO 554	BPP08364
562	CONTINUE	BPP08365
C	DISPLACEMENT FLOW CHANGE	BPP08370
	IF(DIFD.GT.0.0) KA=3.0	BPP08380
	IF(WDIF.GT.0.0) KA=3.5	BPP08390
	CAT=0.5	BPP08400
	GO TO 554	BPP08410
563	CONTINUE	BPP08420
C	NON WETTING FLUID IMBIBITION	BPP08430
	KA=0.0	BPP08440
	IF(DIFD.GT.0.0) KA=2.0	BPP08450
	IF(WDIF.GT.0.0) KA=1.0	BPP08460
	CAT=0.6	BPP08470
	GO TO 554	BPP08490
564	CONTINUE	BPP08491
	IF(WDIF.GT.0.0) KA=3.0	BPP08492
	IF(DIFD.GT.0.0) KA=3.5	BPP08493
	CAT=0.7	BPP08494
	IF(KA.EQ.0.0) GO TO 620	BPP08495
	GO TO 554	BPP08496
570	V=AP(J,K)*X(J,K+74)*TIME	BPP08500
	FLO(J,K)=KA	BPP08510
	IF(KA.EQ.3.0) FLO(J,K)=3.0	BPP08520
	IF(KA.EQ.3.5) FLO(J,K)=3.5	BPP08530
	IF(KA.EQ.4.0) FLO(J,K)=4.1	BPP08540
	IF(KA.EQ.4.2) FLO(J,K)=4.2	BPP08550
	IF(KA.EQ.1.0) FLO(J,K)=3.0	BPP08560
	IF(KA.EQ.2.0) FLO(J,K)=3.5	BPP08570
	IF(CAT.EQ.0.5) FLO(J,K)=4.5	BPP08571
	VOMAX=X(J,K+48)	BPP08580
	VOMIN=0.0	BPP08590
	IF(GC.LT.0.0) VOMIN=0.04*VOMAX	BPP08600
	IF(GC.GE.0.0) VOMAX=0.96*VOMAX	BPP08610
	IF(X(J,K+56).GT.VOMAX) VOMAX=X(J,K+48)	BPP08620
	IF(X(J,K+56).LT.VOMIN) VOMIN=0.0	BPP08630
	VWMAX=X(J,K+48)-VOMIN	BPP08640
	VWMIN=X(J,K+48)-VOMAX	BPP08650
	VOLO=VOMAX-X(J,K+56)	BPP08660
	VOLW=X(J,K+56)-VOMIN	BPP08670
	CASE=0.0	BPP08680
	IF(DIFD.GT.0.0) V=X(J,K+102)	BPP08690
	IF(WDIF.GT.0.0) V=X(J,K+94)	BPP08700

## SOURCE STATEMENT

	IF(WDIF.GT.0.0) GO TO 601	BPP08710
	IF(DIFO.GT.0.0) GO TO 603	BPP08720
	WATER EXCESS	BPP08730
C	601 IF(V.GT.WDIF) GO TO 6.2	BPP08740
	WDIF=WDIF-V	BPP08750
	X(J,K+94)=0.0	BPP08760
	X(J,K+102)=X(J,K+102)+V	BPP08770
	IF(V.LT.VOLW) GO TO 11	BPP08780
	FLO(J,K)=2.0	BPP08790
	VDF(J,K)=VDMIN	BPP08800
	GO TO 554	BPP08810
	11 VDF(J,K)=X(J,K+56)-V	BPP08820
	GO TO 12	BPP08830
	602 VDF(J,K)=VDMIN	BPP08840
	IF(VOLW.GT.WDIF) VDF(J,K)=X(J,K+56)-WDIF	BPP08850
	IF(VOLW.LT.WDIF) FLO(J,K)=2.0	BPP08860
	IF(GC.LT.0.0.AND.FLO(J,K).EQ.2.0) FLO(J,K)=4.5	BPP08870
	X(J,K+94)=X(J,K+94)-WDIF	BPP08880
	X(J,K+102)=X(J,K+102)+WDIF	BPP08890
	WDIF=0.0	BPP08900
	12 CONTINUE	BPP08910
	SO=VDF(J,K)/X(J,K+48)	BPP08920
	IF(FLJ(J,K).EQ. 4.5.AND.GC.GT.0.0) CASE=0.5	BPP08930
	IF(CASE.EQ.0.5.AND.SO.LT.0.80) FLO(J,K)=4.1	BPP08940
	IF(FLO(J,K).EQ.+2.0R.FLO(J,K).EQ.4.1) BASE=1.0	BPP08950
	IF(BASE.EQ.1.0.AND.GC.GE.0.0) CASE=1.0	BPP08960
	IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=2.0	BPP08970
	IF(CASE.EQ.1.0.AND.SO.GE.0.8) FLO(J,K)=4.5	BPP08980
	IF(CASE.EQ.2.0.AND.SO.LE.0.2) FLO(J,K)=4.5	BPP08990
	CASE=0.0	BPP09000
	BASE=0.0	BPP09010
	IF(WDIF.NE.0.0) GO TO 554	BPP09020
	GO TO 590	BPP09030
C	OIL EXCESS	BPP09040
	603 IF(V.GT.DIFO) GO TO 6.4	BPP09050
	DIFO=DIFO-V	BPP09060
	X(J,K+94)=X(J,K+94)+V	BPP09070
	X(J,K+102)=0.0	BPP09080
	IF(V.LT.VOLO) GO TO 13	BPP09090
	VDF(J,K)=VDMAX	BPP09100
	FLO(J,K)=1.0	BPP09110
	IF(GC.GT.0.0) FLO(J,K)=4.5	BPP09120
	GO TO 554	BPP09130
	13 VDF(J,K)=X(J,K+56)+V	BPP09140
	GO TO 14	BPP09150
	604 VDF(J,K)=VDMAX	BPP09160
	IF(VOLO.GT.DIFO) VDF(J,K)=X(J,K+56)+DIFO	BPP09170
	IF(VOLO.LT.DIFO) FLO(J,K)=1.0	BPP09180
	IF(GC.GE.0.0.AND.FLO(J,K).EQ.1.0) FLO(J,K)=4.5	BPP09190
	X(J,K+102)=X(J,K+102)-DIFO	BPP09200
	X(J,K+94)=X(J,K+94)+DIFO	BPP09210
	DIFO=0.0	BPP09220
	14 CONTINUE	BPP09230
	SO=VDF(J,K)/X(J,K+48)	BPP09240
	IF(FLJ(J,K).EQ.4.5.AND.GC.LE.0.0) CASE=0.5	BPP09250
		BPP09260

## FORTRAN SOURCE LIST UB 5

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## SOURCE STATEMENT

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IF(CASE.EQ.0.5.AND.SO.GT.0.2)FLO(J,K)=4.2
IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.4.1)BASE=1.0
IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=1.0
IF(BASE.EQ.1.0.AND.GC.GE.0.0)CASE=2.0
IF(CASE.EQ.1.0.AND.SO.LE.0.2) FLO(J,K)=4.5
IF(CASE.EQ.2.0.AND.SO.GE.0.8) FLO(J,K)=4.5
BASE=0.0
CASE=0.0
IF(DIFO.NE.0.0) GO TO 554
590 CONTINUE
620 IF(DIFO.LE.0.10E-10)DIFO=0.0
IF(WDIF.LE.0.10E-10)WDIF=0.0
IF(DIFO.EQ.0.0.AND.WDIF.EQ.0.0)GO TO 630
ACE=ACE+1.0
DO 35 K=1,8
35 C(K)=0.0
CAT=0.3
KA=4.5
IF(ACE.EQ.1.0)GO TO 554
630 IF(WDIF.NE.0.0.OR.DIFO.NE.0.0)PRINT690,DIFO,WDIF
RETURN
END

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3PP09270  
8PP09280  
8PP09290  
3PP09300  
3PP09310  
3PP09320  
8PP09330  
8PP09340  
8PP09350  
3PP09360  
8PP09370  
8PP09380  
8PP09381  
3PP09382  
8PP09383  
8PP09384  
3PP09385  
3PP09386  
8PP09387  
8PP09390  
3PP09400  
8PP09410

FORTRAN PROGRAM UB 5

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## FUNCTION SUBPROGRAM REFERENCES

IBMAP ASSEMBLY UB 5

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MESSAGES FOR ABOVE ASSEMBLY

## FORTRAN SOURCE LIST

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## SOURCE STATEMENT

IBFTCSUB 6	3PP09420
SUBROUTINE PDIF	BPP09430
COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,	BPP09440
1XA,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID	BPP09450
FILL PRESS DIFFERENTIALS FOR ALL TUBES AT EACH NODE POINT	3PP09460
J=IJ	BPP09470
IK=IJ/JR+1	BPP09480
JK=IJ-JR*(IK-1)	3PP09490
IF(JK.LE.0)IK=IK-1	3PP09500
IF(JK.LE.0)JK=JR	BPP09510
35 FORMAT(1X,21F)	3PP09520
X(J,74)=EP(IK,JK)	BPP09530
IF(IK.EQ.1)GO TO 87	BPP09540
IF(JK.EQ.1)GO TO 92	BPP09550
IF(IK.EQ.IR)GO TO 96	BPP09560
IF(JK.EQ.JR)GO TO 100	BPP09570
X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)	3PP09580
X(J,66)=EP(IK,JK)-EP(IK,JK+1)	BPP09590
X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)	BPP09600
X(J,68)=EP(IK,JK)-EP(IK+1,JK)	3PP09610
X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)	BPP09620
X(J,70)=EP(IK,JK)-EP(IK,JK-1)	BPP09630
X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)	BPP09640
X(J,72)=EP(IK,JK)-EP(IK-1,JK)	3PP09650
GO TO 102	BPP09660
37 IF(JK.EQ.1)GO TO 88	BPP09670
IF(JK.EQ.JR)GO TO 90	BPP09680
X(J,65)=0.0	BPP09690
X(J,66)=0.0	BPP09700
X(J,70)=0.0	BPP09710
X(J,71)=0.0	BPP09720
X(J,72)=0.0	BPP09730
X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)	BPP09740
X(J,68)=EP(IK,JK)-EP(IK+1,JK)	3PP09750
X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)	3PP09760
GO TO 102	BPP09770
88 X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)	BPP09780
DO 89 K=1,8	BPP09790
IF(K.EQ.3)GO TO 89	BPP09800
X(J,K+64)=0.	BPP09810
89 CONTINUE	BPP09820
GO TO 102	BPP09830
90 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)	3PP09840
DO 91 K=1,8	BPP09850
IF(K.EQ.5)GO TO 91	BPP09860
X(J,K+64)=0.	BPP09870
91 CONTINUE	3PP09880
GO TO 102	BPP09890
92 IF(IK.EQ.IR)GO TO 94	BPP09900
X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)	BPP09910
X(J,66)=EP(IK,JK)-EP(IK,JK+1)	BPP09920
X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)	BPP09930
DO 93 K=4,8	BPP09940
X(J,K+64)=0.0	BPP09950
93 CONTINUE	BPP09960

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## SOURCE STATEMENT

16	GO TO 102	BPP0997
17	94 X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)	BPP0998
20	DO 95 K=2,8	BPP0999
21	X(J,K+64)=0.0	BPP10000
22	95 CONTINUE	BPP10001
24	GO TO 102	BPP10002
25	96 IF(JK.EQ.JK) GO TO 98	BPP10003
30	X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)	BPP10004
31	X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)	BPP10005
32	X(J,72)=EP(IK,JK)-EP(IK-1,JK)	BPP10006
33	DO 97 K=2,8	BPP10007
34	X(J,K+64)=0.0	BPP10008
35	97 CONTINUE	BPP10009
37	GO TO 102	BPP10010
38	98 X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)	BPP10011
39	DO 99 K=1,8	BPP10012
40	IF(K.EQ.7) GO TO 99	BPP10013
41	X(J,K+64)=0.0	BPP10014
42	99 CONTINUE	BPP10015
43	GO TO 102	BPP10016
44	100 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)	BPP10017
45	X(J,71)=EP(IK,JK)-EP(IK,JK-1)	BPP10018
46	X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)	BPP10019
47	X(J,72)=0.0	BPP10020
48	DO 101 K=1,4	BPP10021
49	X(J,K+64)=0.0	BPP10022
50	101 CONTINUE	BPP10023
51	102 CONTINUE	BPP10024
52	C FILL POSITIVE DIFFERENTIAL PR. AND CAP. PR.	BPP10025
53	DO 104 K=1,8	BPP10026
54	VDF(J,K)=0.0	BPP10027
55	AP(J,K)=0.0	BPP10028
56	IF(X(J,K).EQ.0.0) GO TO 104	BPP10029
57	X(J,K+64)=X(J,K+64)+X(J, K+84)	BPP10030
58	IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)	BPP10031
59	104 CONTINUE	BPP10032
60	RETURN	BPP10033
61	END	BPP10034

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MESSAGES FOR ABOVE ASSEMBLY



## FORTRAN SOURCE LIST

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## SOURCE STATEMENT

\$IBFTCSUB 7	BPP10350
SUBROUTINE SIMU	BPP10360
C PROGRAM SIMU	BPP10370
COMMON/SYMARG/X(50,16),AP(50,8),GC,VD,VW,TIME,VDF(50,8),IJ,IR,JR,	BPP10380
1XA,EP(15,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID	BPP10390
COMMON/SDLC/ADD,CP,JIM,ICP	BPP10400
COMMON/SIM/COM(15),RAD(15),KL,LK	BPP10410
DIMENSION D(5,3)	BPP10420
FACT=5894731.0*1.35/1.732	BPP10430
DO 50 J=1,JR	BPP10440
DO 60 I=1,IR	BPP10450
ISK=(1-I)*JR+J	BPP10460
DO 20 M=1,8	BPP10470
X(ISK,M+8)=1.0	BPP10480
X(ISK,M+16)=1.0	BPP10490
X(ISK,M+24)=1.0	BPP10500
X(ISK,M+32)=1.0	BPP10510
X(ISK,M+40)=1.0	BPP10520
X(ISK,M+48)=1.0	BPP10530
X(ISK,M+56)=1.0	BPP10540
X(ISK,M+64)=1.0	BPP10550
20 CONTINUE	BPP10560
X(ISK,73)=1.0	BPP10570
X(ISK,74)=1.0	BPP10580
IF(J.EQ.JR) GO TO 120	BPP10590
DO 70 K=1,4	BPP10600
RN=RDY1(Y)	BPP10610
DO 75 M=1,LK	BPP10620
IF(RN.LE.COM(M)) GO TO 100	BPP10630
75 CONTINUE	BPP10640
100 X(ISK,K)=RAD(M)	BPP10650
70 CONTINUE	BPP10660
GO TO 130	BPP10670
120 DO 160 K=1,4	BPP10680
X(ISK,8)=0.0	BPP10690
160 CONTINUE	BPP10700
X(ISK,8)=0.0	BPP10710
130 IF(J.NE.1) GO TO 150	BPP10720
DO 165 K=4,8	BPP10730
X(ISK,K)=0.0	BPP10740
155 CONTINUE	BPP10750
150 IF(I.NE.1) GO TO 155	BPP10760
X(ISK,1)=0.0	BPP10770
X(ISK,2)=0.0	BPP10780
X(ISK,6)=0.0	BPP10790
X(ISK,7)=0.0	BPP10800
X(ISK,8)=0.0	BPP10810
155 IF(I.NE.IR) GO TO 180	BPP10820
DO 195 K=2,6	BPP10830
X(ISK,K)=0.0	BPP10840
195 CONTINUE	BPP10850
C FILL ALL TUBE RADII	BPP10860
180 IF(J.EQ.1) GO TO 190	BPP10870
DO 135 N=1,3	BPP10880
IF(I.EQ.1.AND.N.NE.1) GO TO 135	BPP10890

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## SOURCE STATEMENT

	IF(I.EQ.IR.AND.N.NE.3) GO TO 135	BPP10900
	IP=I-N+2	BPP10910
	IS=(IP-1)*JR+J-1	BPP10920
	X(ISK,N+4)=X(IS,N)	BPP10930
135	CONTINUE	BPP10940
	IF(I.EQ.1) GO TO 190	BPP10950
	IS=(I-2)*JP+J	BPP10960
	X(ISK,3)=X(IS,4)	BPP10970
190	CONTINUE	BPP10980
C	FILL LENGTH IN 9-15	BPP10990
	DO 280 K=9,15	BPP11000
	X(ISK,9)=1.4142	BPP11010
	IF(X(ISK,K-1).EQ.1.0) X(ISK,K)=1.4142	BPP11020
280	CONTINUE	BPP11030
C	FILL OIL AND WATER CONDUCTIVITIES IN 33-40 AND 41-48 RESPECTIVELY	BPP11040
	DO 300 K=1,8	BPP11050
	X(ISK,K+8)=X(ISK,K+8)*GRID	BPP11060
	B(ISK,K)=(FACT*X(ISK,K)**4)/X(ISK,K+8)	BPP11070
	X(ISK,K+32)=B(ISK,K)/VO	BPP11080
	X(ISK,K+40)=B(ISK,K)/VW	BPP11090
C	COMPUTE VOLUMES OF TUBES	BPP11100
	X(ISK,K+48)=3.0*1.732*X(ISK,K+8)*X(ISK,K)**2.0	BPP11110
C	FILL FLOW OF OIL IN ALL TUBES 75-64	BPP11120
	X(ISK,K+56)=X(ISK,K+48)	BPP11130
	X(ISK,K+74)=X(ISK,K+32)	BPP11140
	X(ISK,K+84)=0.0	BPP11150
	X(ISK,K+94)=0.0	BPP11160
	X(ISK,K+102)=0.0	BPP11170
	X(ISK,K+110)=0.0	BPP11180
	X(ISK,K+118)=0.0	BPP11190
	X(ISK,K+128)=0.0	BPP11200
	X(ISK,K+136)=0.0	BPP11210
	X(ISK,K+144)=0.0	BPP11220
	X(ISK,K+152)=0.0	BPP11230
	IF(X(ISK,K).EQ.0.0) X(ISK,K+24)=2.0	BPP11240
300	CONTINUE	BPP11250
	X(ISK,88)=0.0	BPP11260
	X(ISK,84)=0.0	BPP11270
	X(ISK,92)=0.0	BPP11280
	X(ISK,94)=0.0	BPP11290
	X(ISK,127)=0.0	BPP11300
	X(ISK,128)=0.0	BPP11310
C	ASSIGN VALUES TO DEL PR IN 65-72	BPP11320
	IAN=IR-1	BPP11330
	AN=IAN	BPP11340
	Z=CP/AN	BPP11350
	DO 301 K=3,5	BPP11360
	X(ISK,K+64)=Z	BPP11370
301	CONTINUE	BPP11380
	X(ISK,71)=-Z	BPP11390
	X(ISK,72)=-Z	BPP11400
	X(ISK,65)=-Z	BPP11410
	X(ISK,66)=0.0	BPP11420
	X(ISK,70)=0.0	BPP11430
C	ASSIGN PRESSURE 74	BPP11440

## FORTRAN SOURCE LIST UB 7

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## SOURCE STATEMENT

5 Y=1  
 6 YS=IR  
 7 X(ISK,74)=CP\*(YS-Y)/(YS-1.0)  
 0 IJ=(I-1)\*JR+J  
 1 1 FORMAT(5X,8E15.7)  
 2 50 CONTINUE  
 4 50 CONTINUE  
 6 RETURN  
 7 END

BPP1145  
 BPP11460  
 BPP11470  
 BPP1148  
 BPP1149  
 BPP11500  
 BPP11510  
 BPP1152  
 BPP11530

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## FORTRAN PROGRAM UB 7

## FUNCTION SUBPROGRAM REFERENCES

IBMAP ASSEMBLY UB 7

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## MESSAGES FOR ABOVE ASSEMBLY

IBLDR -- JOB 000000

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\*\*\* OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT 08 HRS. 32 MTS. 02 SECS